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JPRS L/9269

25 August 1980

Translation

LABORATORY ON THE SEA BOTTOM

By

Pavel Andreyevich Borovikov

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JPRS L/9269

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LABORATORY ON THE SEA BOTTOM

Leningrad LABORATORIYA NA MORSKOM DNE in Russian 1977 signed to press 22 Apr 77 pp 1-135

[Book by Pavel Andreyevich Borovikov, Gidrometeoizdat, 50,000 copies]

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PUBLICATION DATA

English title	: LABORATORY ON THE SEA BOTTOM
Russian title	: LABORATORIYA NA MORSKOM DNE
Author (s)	: Pavel Andreyevich Borovikov
Editor (s)	: L. A. Zel'manova
Publishing House	: Gidrometeoizdat
Place of Publication	: Leningrad
Date of Publication	: 1977
Signed to press	: 22 April 1977
Copies	: 50,000
COPYRIGHT	: L., Gidrometeoizdat, 1977.

ANNOTATION

[Text] The author of this book, one of the designers of the Chernomor Undersea Laboratory, has for many years directly participated in organization and conduct of undersea research. Ignoring the "sensational" side of man's life under water, he tells of those unique opportunities presented to oceanographers by a research laboratory sited on the ocean floor. In this book the author endeavors to analyze and synthesize worldwide experience in utilization of manned habitats and research equipment and to relate the working methods of the underwater scientist.

This book is intended for persons professionally involved with the sea as well as for the general reader.

PROLOGUE

Gathering of information with the aid of specialized oceanographic vessels is the principal means of studying the ocean today. Traveling to the investigation area, a vessel lowers into the water various instruments and devices to measure the characteristics of the undersea environment and to collect samples of water, soil, as well as specimens of living organisms.

This method, due to its organizational simplicity and comparatively low cost, is fully justified when working in new areas, in investigations aimed at obtaining information on space-time parameters of the most general nature. As such information is gathered, scientists pinpoint in the target area smaller areas with certain anomalies which merit special attention. More detailed investigations begin in these smaller areas, involving not only oceanographic vessels but also a great many other platforms carrying equipment and investigators -- aircraft, satellites, and submersibles. In the last 10-15 years means of oceanic investigation have been developed which carry men beneath the sea, directly to the target of scientific investigation.

When diving beneath the sea, man enters a different world, an environment in which he cannot exist. In order to protect himself against the effect of water and in order to live and work under the sea, man was compelled to develop special equipment.

There exist two categories of such equipment. One encompasses systems which provide man with conditions close to those to which he is accustomed on land -- atmospheric pressure, air as a breathing mixture, a comfortable temperature and humidity. These devices are called manned submersibles.

The second category encompasses diving systems, in utilization of which man is subjected to elevated pressure which is equal or close to the pressure of the ambient water environment. Living conditions for man in such systems differ sharply from those to which we are accustomed on land: pressure of the gaseous medium in which the diver finds himself reaches dozens of atmospheres, the breathing mixture contains helium in place of nitrogen, and even food tastes different from normal in this environment.

Considerable attention is devoted both in this country and abroad to designing, building and operating manned submersibles. A great many books, magazine articles and surveys have been written on this subject. There also exist a number of publications dealing with the results of expeditions on which oceanographic research has been conducted with the aid of manned submersibles.

Oceanic research employing diving systems has enjoyed considerably less success. Except for a few fragmentary reports and a small number of articles on particular topics in scientific journals, there are no materials on this topic which are available to the general oceanographic scientist and engineer community. It would therefore apparently be useful, before proceeding with the main subject of this book, to review presently-existing methods of underwater diving operations.

The simplest and oldest technique is diver descent from the surface. The diver goes under water from the deck of a ship, works on the bottom for a certain period of time, and then ascends to the surface. His rate of ascent depends both on the depth of dive and on total time spent on the bottom. A diver's ascent-to-surface time -- decompression time -- often greatly exceeds working time on the bottom, and therefore this method of conduct of diver activities is effective only at shallow depths.

The appearance of specialized diving tenders, carrying decompression chambers and diving bells, eliminated the necessity for a diver to undergo the long decompression process in the water. Having completed his work on the bottom, a diver enters a bell lowered from the ship, closes and seals the bottom hatch, and forces water out of the bell with compressed air. Then the diving bell, with the diver inside, rapidly ascends to the surface, is hoisted on board the diving tender, and is hermetically linked up to the shipboard decompression chamber. A pressure equal to pressure in the diving bell at the working depth is established in advance in the decompression chamber. After the bell is linked up to the shipboard decompression chamber, the diver enters the chamber, removes his gear and rests there until pressure in the chamber is gradually brought down to atmospheric. This diving method eases conditions of diver decompression, but it does not substantially reduce decompression time.

Both these methods, although the second method is clearly more in conformity with the modern level of technology then the first method, are basically an anachronism. Both are based on utilization of ventilated diving gear, which has remained practically unchanged since the end of the 19th century; the rubber has improved, the diving helmet faceplate has become more transparent, and a greater number of different valves have been added, but on the whole the degree of sophistication of this diving gear is the same as many years ago.

Discovery of the "saturation effect" in the 1960's -- a method enabling man to remain under pressure for an extended time -- served as an impetus for a genuine revolution in diving technology. After the possibility of man remaining an extended period under pressure was proven theoretically and practically, several fundamentally new versions of conduct of diving activities were developed.

One such technique involves diver descents based on utilization of those same shipboard diving systems, consisting of a stationary decompression chamber and connecting diving bell. This method differs from the previous one, however, in that divers remain for an extended time in the shipboard decompression chamber at a pressure equal or close to water pressure at the working depth. Twice every 24 hours they enter the diving bell, which is hermetically connected to the decompression chamber and which contains an interior pressure equal to pressure in the compartments of the decompression chamber, and close the hatches between bell and chamber. Then the bell is disconnected from the decompression chamber and lowered to the working depth, where the divers open the hatch and enter the water. Upon completion of the work period, the divers reenter the bell and close the hatch; the bell is raised to the surface, linked up to the decompression chamber, and the divers transfer into the latter to rest. This goes on for days and weeks -- until work on the bottom is completed, after which the divers finally undergo a single decompression process.

Employment of such a method involving personnel remaining for an extended period of time under pressure has sharply increased the efficiency of deep-water diving operations -- in certain cases 10-fold and more, and today this technique is being increasingly more extensively employed.

Another method of handling diving operations consists in employment of fixed underwater base-laboratories. Such a base-laboratory is an underwater home for divers. It contains everything necessary for normal life routine and activities -- sleeping compartments, wardroom with television set, library, radio receiver, galley stocked with provisions and an electric stove, shower and toilet, diving gear lockers, and laboratories. All compartments are filled with an artificial breathing mixture at a pressure equal to water pressure on the laboratory's exterior, so that the diver or, as the inhabitants of such an undersea habitat are called, the aquanaut merely dives through a hatch and is at his work station -- on a seafloor object of investigation, for example. Such habitats are designed for man to remain under water for many days at a time.

And finally, there exists another method of diver operations. It is based on utilization of self-contained self-propelled submarine units containing two high structural-strength compartments. Normal atmospheric pressure is maintained in the control compartment, which contains the steering controls and job supervisor. The other compartment is for the divers. The device dives, approaches the work site, and settles onto the sea floor. The divers equalize pressure in their compartment with the outside pressure, open the hatch and enter the water, while the job supervisor monitors their actions from the control compartment. When the job is finished, the divers return to their compartment, close the hatch, and the craft ascends to the surface. This is essentially nothing other than a self-contained, self-propelled diving bell, but the device's self-sufficiency and self-propulsion capability so extend the diver's underwater work capabilities that this method can be considered a separate method.

To recapitulate, there are five methods of working under water. Which of these have taken their place in the arsenal of oceanographic researchers? Let us turn to worldwide statistics on undersea research.

The absolute majority of observations conducted under water by oceanographers have involved diving from the surface, that is, organizationally the simplest method. Prior to practical adoption of the aqualung or scuba gear in underwater activities, which took place in the 1950's, very few individuals undertook dives for the conduct of scientific investigations. Simple, reliable and safe scuba gear enabled thousands of oceanographers to observe the undersea world and the object of investigation with their own eyes. Very often what they saw differed significantly from their hypothetical assumptions, which were based on the results of analysis of samples collected from the surface. This especially applies to biological, geological, and geomorphological observations.

The above-described new diving methods were adopted into diving practice in many countries in the 1960's. This was caused by various factors. In the United States, for example, loss of the nuclear submarine "Thresher" served as the impetus for undersea technology in general and diving equipment and techniques in particular, while in France it was development of offshore oil drilling, which was particularly important for France, since it possesses practically no oil of its own.

The new equipment and new underwater working methods drew the attention of oceanographers. Scientists participated in practically all the first experiments with undersea habitats ("Precontinent," "Sealab," etc).

Two scientists from the Scripps Oceanographic Institute took part in dives to a depth of 183 meters conducted by the U.S. company Westinghouse Electric. A pressurized shipboard habitat unit and a diving bell were utilized in these experiments.

Oceanographers also participated in 1968 tests of the "Deep Diver" submarine with diver compartment. The submarine proceeded above the seabed at a depth of 130 meters, while its crew, gazing through viewing ports, selected a work site. Spotting a seabed area which was especially rich in marine life, the crew eased the craft onto the seafloor, diver-biologists exited into the water, examined the seabed around the submarine, and collected samples of interest to them.

Subsequently, however, the "tastes" of oceanographers have become increasingly more specific. Although investigations conducted at shallow depths with employment of scuba gear, which have now become traditional, continue to be widely practiced, experiments with undersea laboratories utilized as a base for conduct of undersea investigations are being repeated year after year and are taking on an increasingly oceanographic "bias."

As far as is known at the present time, only one comparatively large program of undersea observations was conducted off the coast of Canada with the aid of the "Deep Diver" submarine, which permits divers to exit while submerged. And nothing is known of any utilization of shipboard diving systems for the conduct of oceanographic observation (it is true that this may be due to the fact that no such vessels are at the disposal of oceanographers).

In 1972 scientists at the University of New Hampshire asked 160 American oceanographers to grade with a 10-point system the principal diving methods of ocean research. The result of the grading, converted into a table, indicated that the most convenient method of performing such investigations is employment of manned undersea laboratories in one form or another. World-wide practice confirms this view.

In this book we have endeavored to discuss in an objective manner the principal aspects of the problem of utilization of undersea laboratories and to define their place in the overall arsenal of technical devices for oceanographic research. The book consists of individual scholarly publications, reports on experiments conducted with undersea laboratories, and information obligingly furnished to the author by Soviet and foreign scientists. Main emphasis in this book is placed on description of oceanographic research conducted by the crews of undersea laboratories and the results of this research, although considerable attention is also focused on problems of organization of the activities of undersea laboratories, preparation of scientific programs, and selection of teams of investigators.

The author would like to express his thanks to staff members of the USSR Academy of Sciences Oceanographic Institute imeni P. V. Shirshov: Doctor of Technical Sciences V. S. Yastrebov, Candidate of Technical Sciences V. P. Nikolayev, Doctor of Chemical Sciences E. A. Ostroumov, Candidate of Geographical Sciences N. A. Aybulatov, and Candidate of Biological Sciences L. I. Moskalev, as well as to A. V. Ignat'yev of the Leningrad Hydrometeorological Institute, who carefully perused the manuscript for this book and made a number of valuable comments.

Chapter 1. HOW IT WAS

First Steps

The first two experiments dealing with an extended stay by man under water were conducted in 1962 by teams led by Jacques Ives Cousteau and Edwin Link. This was followed by a series of experiments in the "Precontinent" (France) and "Sealab" (United States) programs. In 1965 a crew on board the "Precontinent-3" undersea laboratory spent approximately four weeks at a depth of 100 meters, an achievement which has not yet been surpassed up the present day.

The success of the first experiments evoked a "second wave" of experiments with undersea laboratories. These experiments did not pursue any concrete objectives -- their organizers wanted merely to "live for a while" under water and, secondarily, to perform observations which did not require substantial preparation or costly equipment.

Since 1962 more than 50 experiments have been conducted involving personnel remaining under water for several days or more. The Appendix contains data on some of them.

Experiments were directed toward solving several standard problems: work on performance of operations of an undersea-technical nature, both for the benefit of industry and emergency rescue services; conduct of oceanographic research; development of technical sports.

As a rule medical-physiological investigations did not constitute an independent goal but accompanied the majority of experiments.

Technical-sports experiments were conducted by sports diving clubs. Their aim was to encourage the development of technical initiative on the part of club members and to popularize sport diving. The "habitats" built by the clubs were sited at shallow depths -- to 10-12 meters. As a rule an underwater stay was limited to several days, and the habitat crew would be only two or three persons. Examples of undersea "habitats" of this type include "Glaucous" (England), "Caribe" (Czechoslovakia-Cuba), "Malter" (GDR), and "Ikhtiandr" (USSR).

Experiments conducted by the U.S. Navy emergency rescue services pursued the objective of reaching the maximum possible depth of dive, maximum duration spent by a crew under water, and work on operations of an underwater technical nature. Navy experimental programs also sometimes included oceanographic research, but only on a secondary basis. Considerable resources and practically unlimited financing enabled the organizers of military programs to conduct experiments on a large -- and not always justified -- scale. For example, the cost of just 24 hours of operation by the U.S. Navy's Sealab II habitat was 35,000 dollars.

The first experiments involving an extended stay by personnel under water were financed by commercial companies (both private and government-owned) interested in developing equipment and methods of performing work under water. The most typical example of an experiment of this kind is the "Precontinent-3" program: construction and operation of this undersea habitat were financed chiefly by French oil companies.

A subordinate role was assigned to oceanographic research in the first experiments dealing with man living under water, and when programs were cut back, oceanographic research was the first to go. It is obvious, however, that research can produce results only when specially conducted, when the design of an undersea habitat, crew makeup and qualifications, program of activities, in short, everything is tailored specifically to oceanographic research.

We must state that to some extent a certain degree of conservatism by oceanographers, proceeding from their devotion to traditional means was a factor here. The development of underwater laboratories took them unawares to a certain degree, and although oceanographers did participate in the first experiments with undersea habitats, as we have already stated, there was as yet no system in these investigations. In addition, the first experiments in human habitation under water were in many ways of a publicity nature, and the publicity raised by the press around these experiments led to appearance in the press of information which was not always objective or competent. All this could not help but have an effect on the attitude of oceanographers toward this new means of investigating the ocean. Only a few scientists were able to see behind the noisy publicity the very promising substance of the initiated experimental activities.

A second important act of omission by the first experiments consisted in the fact that, in increasing the depth of undersea laboratories, the program organizers somehow immediately bypassed medium depths -- 20-40 meters, going into the twilight zone of 100 meters and more. Surface-adjacent waters, which are the most interesting for oceanography -- mixed by wave action, penetrated by the sun's rays and saturated with life -- were passed over.

As there developed increasing experimentation with underwater habitats, there formed the opinion almost simultaneously in a number of countries that there was a need for organization of specific-purpose oceanographic programs of medium-depth undersea research. Long-term programs of study of the processes taking place in the ocean at a depth of several tens of meters were initiated with the aid of underwater laboratories, at first in this country and subsequently in the United States and the FRG.

The specific features of working at shallow depths subjected to the effect of surface wave action made it necessary to revise practically the entire organization of experiments, from the composition of the breathing mixture and crew decompression procedures to habitat design and structure of support services.

At shallow depths one can utilize for crew breathing a mixture of oxygen with hydrogen, not with helium, as was the case in deep submergences. However, before this new breathing mixture, which differs from atmospheric air only in pressure and ratio of components, was accepted for use in underwater activities, an entire series of experiments with people under shore conditions was undertaken.

These laboratory investigations of nitrogen-oxygen breathing mixtures have not yet been completed. Each experiment, as is usually the case, producing an answer to one question, states several new problems. Nevertheless the "backlog" achieved in the 1960's in the area of physiology of man living in an elevated-pressure nitrogen-oxygen breathing environment made it possible to proceed with direct experiments in the sea, and oceanographers did not let this opportunity slip by.

Above Us Is the Black Sea

In this country research involving extended stays by man under water began at the end of the 1960's. Three undersea research programs involving employment of undersea habitats -- "Ikhtiandr," "Sadko," and "Chernomor" -- originated and began to be elaborated almost simultaneously.

The "Ikhtiandr" program was organized by a group of sports diving enthusiasts in the city of Donetsk. They made their first extended dive in 1966, during which two persons spent approximately four days at a depth of 10 meters off Point Tarkhankut, on the Crimean Black Sea coast. The experiment was interrupted by a storm, but even in this brief period of time they were able to amass a certain amount of experience in working under water. On the basis of this experiment the group's engineers designed and built an undersea laboratory assembled of individual modules. Each module had its specific function -- working spaces, living quarters, diving compartments, etc. By combining different modules in a specific order and sequence, it was possible to assemble underwater habitats containing from two to four work-space and living-quarters compartments.

The "Ikhtiandr" program successfully evolved over the course of three years. In 1969 the "Ikhtiandr" team changed over to designing equipment for underwater work activities and scuba gear.

At the same time as the program was initiated at Point Tarkhankut, the "Sadko" habitat was lowered into the water near Sukhumi. This was the first dive in a "Sadko" undersea research program organized by personnel at the Leningrad Hydrometeorological Institute. The "Sadko" program specified a series of dives by three undersea habitats to sequentially greater depths. In 1966 the "Sadko" habitat operated at a depth of 12.5 meters, in 1967 the "Sadko-2" habitat was placed at a depth of 25 meters, and in 1969 "Sadko-3" habitat aquanauts also worked at a depth of 25 meters, but for a longer period of time than their predecessors. The principal objective of the "Sadko" program was hydrophysical and bioacoustic research.

The "Chernomor" program was organized in 1967 by the USSR Academy of Sciences Institute of Oceanography imeni P. P. Shirshov. The decision to embark upon this program was made following a thorough evaluation of Soviet and foreign experience in man living and working under water and the prospects opened up to oceanographers by the new method of man working under the sea.

It was decided to divide the "Chernomor" undersea research program into two stages. At the first stage the underwater habitat was to be evaluated as a means of studying the ocean, and those areas were to be determined development of which would be most effective with the aid of an underwater habitat. At the second stage oceanographic research proper was to be conducted in selected areas.

Blue Bay on the Black Sea coast of the Caucasus near Novorossiysk was selected for the first phase of the program. Adjacent to the bay were the grounds of the institute's Black-Sea Experimental-Scientific Research Station (now called the Southern Department of the Academy of Sciences Institute of Oceanography).

The "Chernomor" underwater laboratory was the world's first habitat intended specifically for the conduct of oceanographic investigations. Evaluating the experience -- sometimes sad, but more frequently successful -- of their predecessors, the designers of "Chernomor" endeavored to incorporate a number of requirements into its design.

The design of the habitat should offer conditions for normal living and working under water for scientific personnel -- that is, persons of average physical development and diving experience. This meant that the habitat should be sufficiently spacious, comfortable, and should provide a minimum influence of specific conditions of life under water on the physical and emotional well-being of the crew.

Since the laboratory was intended for extended scientific investigations in various areas of the sea, the procedure of placing it on the seafloor and floating it to the surface should be as simple and uncomplicated as possible. Eliminated in advance was employment of any surface tender hoist equipment, since this would make operation of the habitat more complicated and expensive.

The habitat should possess a strong hull, so that crew decompression could be conducted directly in the habitat after bringing it to the surface.

The pressure hull and basic systems should be designed for operation down to depths of 30-40 meters, that is, within the proposed range of utilization of nitrogen-oxygen breathing mixtures.

The habitat should possess not less than a 24-hour self-sufficiency in all parameters for greater operational safety.

In the 1968 season -- the undersea habitat's first season -- it was decided to restrict operations to a working depth of 12 meters, which would make it possible to employ compressed air for breathing. It was also decided that investigations conducted from the undersea laboratory should be primarily of a methods character.

The "Chernomor" undersea habitat was launched in the summer of 1968. After all its systems were tested at depths of 5 and 12 meters, the aquanauts proceeded with performance of scientific investigations.

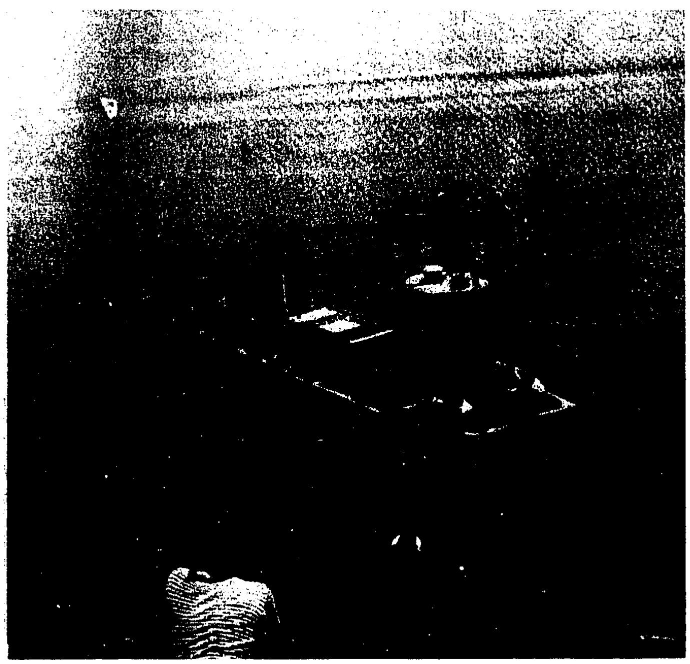
During a period of several months in 1968, five scientific teams, the members of which spent a total of approximately 100 days under waters, lived and worked in the "Chernomor" undersea habitat at depths of 10-14 meters. The aquanauts performed investigations in hydrooptics, hydrology biology, and geology. During the course of research activities the habitat was moved on several occasions from one seafloor site to another, depending on the research objectives.

Analysis of the results of the first year of operation of the habitat indicated that the volume of worked performed exceeded the framework of purely methodological investigations; in a number of instances the aquanauts obtained data of independent scientific interest. At the same time the people at the institute concluded that although possibilities of conducting research from an undersea habitat base are quite extensive, the work area -- the northern part of the Black Sea coast of the Caucasus -- imposes a number of limitations on research subject matter. This area is characterized by a gently-sloping sandy seafloor with few rock outcrops, and with a paucity of flora and fauna. Therefore conduct of biological and hydrochemical investigations in this area was acknowledged to be inadvisable. The oceanographer organizers of the research program decided to concentrate their attention on hydrooptical measurements and study of the specific features of the lithodynamics of sandy seafloor at medium depths -- to 30 meters. It was also proposed that these investigations be accompanied by measurements of the hydrodynamic background: the state of the sea surface and distribution of current velocities and directions.

Precisely these two areas of investigation became traditional for the entire "Chernomor" program. The purpose of the hydrooptical investigations was to construct a statistical model -- a unique atlas -- of distribution of the natural light field under water at depths to 30-35 m. The lithodynamic program aimed at determining the boundaries and degree of activity of lithodynamic processes on sandy seafloor at these same depths.

On-site work was performed chiefly in the summer and fall months, while the habitat would overwinter on shore. Each season's working experience suggested to institute engineers the need for various modifications and improvement in the habitat's design and construction. In 1970 "Chernomor" assumed a final form, and from that time henceforth the laboratory's appearance remained practically unchanged. This modified habitat was designated "Chernomor-2m."

Design and construction of "Chernomor-2m" has been described in many books and magazine articles, and therefore there is no need to go into detail here.



"Chernomor-2m" Undersea Habitat After Surfacing.

A special vessel served as support ship for the "Chernomor" -- the approximately 400-ton refitted medium fishing trawler "Akademik L. Orbeli." The tender carried on board a PDK-3 standard decompression chamber, high-pressure compressors, 400-liter compressed air and nitrogen tanks, and a power generator. When the undersea habitat was on the seafloor, the tender would maintain position over it with four mooring buoys placed in advance at the dive site.

Twelve scientific teams worked on board the "Chernomor" from the day the undersea habitat went into operation in 1968 up to program completion in 1974; personnel included more than 40 oceanographers, who spent a total of more 760 days at depths from 10 to 31 meters.

Living Quarters and Central Control Compartment of "Chernomor-2m" Undersea Habitat.

In the 1968-1972 seasons the habitat was placed on the seafloor in the Blue Bay area near Novorossiysk, at a distance of 1.5 kilometers from the shore. The seafloor in this area slopes gently, with a gradient of approximately 0.027. The bottom is sand-covered to a depth of 25 meters, beyond which the sand begins to be replaced by a solid cover of broken and whole shells; The first signs of silting on the seafloor appear at depths of about 30 meters, while a clearly-marked silt boundary occurs at a depth of 40 meters. Occasional rock outcrops are covered by heavy growth of rockweed of the genus Cystoseira to a depth of 25 meters.

Prevailing winds in the Blue Bay area are northerlies, southerlies, southwesterlies, and westerlies. Maximum swell comes from the west and southwest, and can reach a height of 4 meters and more.

"Chernomor-2m" Aquanaut in Diving Compartment Prepares to Enter the Water.

In 1973-1974 the undersea habitat and its tender took part in the joint Bulgarian-Soviet "Shel'f-Chernomor" expedition. The expedition worked in

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000300020041-1

territorial waters of the People's Republic of Bulgaria, with a multinational team of scientists from the USSR, Bulgaria, and the GDR. Both crews were also international: each contained three Soviet and two Bulgarian scientists.

The work in Bulgaria was performed in an area south of Burgas, off Point Maslen. The habitat was sited 300-400 meters from shore, at a depth of 18-19 meters.

The research program in 1973-1974, in addition to traditional observations pertaining to lithodynamics of sandy seafloor and hydrooptics, encompassed investigations of seafloor primary productivity and acclimation of freshwater trout to marine conditions.

The considerable volume of scientific information gathered by these teams manning the "Chernomor" undersea habitat was due, in addition to other factors, to the unprecedented length of its continuous operation: during a period of 7 years straight the habitat served as a base for oceanographers studying the sea "from the inside."

The 1974 expedition season was the last one for the "Chernomor" undersea habitat. The habitat hull and systems had experienced considerable wear and tear during the years of intensive utilization, requiring a major overhaul.

Therefore the "Chernomor-2m" habitat was retired from service and turned over for safekeeping and exhibit to the Marine Museum of the city of Varna, while the team of engineers at the Institute of Oceanography turned their attention to new tasks. There were two: construction of a new, "Chernomor-3" sea habitat, and an on-land deep-sea dive simulator.

In view of the development prospects of undersea research, it was decided to begin with the on-land simulator, which would constitute a unique test bench and training facility. The bulk of the assembly and adjustment work was performed in 1974-1975, and experimental operation of the simulator began in 1976.

Its systems and equipment provide a capability to simulate dives to a depth of 300 meters, employing helium-oxygen breathing mixtures.

Work on designing the "Chernomor-3" undersea habitat was in progress in parallel with development of the dive simulator. The new habitat will be larger than its predecessors -- it will have a six-man crew, have a displacement of more than 200 tons, and a working depth in excess of 100 meters.

Bringing the "Chernomor-3" deep-water habitat on-stream will signify a new stride forward in the evolution and development of undersea oceanographic research.

The "Helgoland" Program

In the Federal Republic of Germany an oceanographic research program employing an undersea habitat was begun in 1968, when Professor Kinne, director of the Biological Institute on the Island of Helgoland, working jointly with Professor Ruff, director of the Institute of Aerospace Medicine, requested funds from the government of the FRG to finance construction and outfitting of an undersea habitat.

On 22 August 1968 the German branch of the international firm Babcock and Wilcox signed a contract to build a habitat, and at the end of September the undersea laboratory was delivered to the site of its first immersion -- Flensburg Inlet, and on 20 September it was lowered to the floor of the inlet, to a depth of 10 meters, by its support vessel, the "Friedrich Heinke" (309 tons gross displacement).

The undersea habitat, designated the "BACH-1," comprised a horizontal cylinder 6 meters in length and 2 meters in diameter, resting on the seafloor on four supports. Ballast tanks formed watertight bulkheads at the two ends of the pressure hull. The rest of the hull was divided into two habitat compartments, a diving compartment and living quarters, separated by a bulkhead. The living quarters contained a table, bunks, electrical equipment switchboard, water and food stores. The diving compartment, in addition to an exit well, contained the air-gas system distribution panel, all diving gear, and toilet. Habitat total displacement was approximately 20 tons, and electrical equipment total power requirements were approximately 3 kilowatts.

During 1968 operations, all life-support supplies for the two-man crew -- air, electricity, food and water -- were supplied from a special vessel. The aquanauts worked according to a program prepared by the Biological Institute, and the results of their investigations were promising. Weather problems, however, caused a good deal of trouble to the support services. The tender drifted on its anchors due to the swell, and on several occasions it was necessary to extend the cable-hose leading to the underwater habitat. Therefore upon completion of the experiment Professor Kinne raised the question of building a new undersea habitat. Based on the operating experience of the "BACH-1," he stated the following requirements:

the working range of habitat depth should be not less than 30 meters;

the habitat should have a maximum degree of self-sufficiency;

the habitat should be sited as far as possible from shipping lanes, underwater work areas, and fisheries;

the habitat and research areas located alongside it should be equipped with emergency systems and shelters; the adjacent water area should be marked off and divided into grid squares;

a system of fixed holding facilities for keeping and raising living organisms should be adopted.

In November 1968 the West German Government appropriated 1 million marks for construction of a new undersea habitat, and the Dreger Company contracted to build it. Work began immediately, and the underwater habitat was completed by 1 July 1969. The total cost of construction was greater than 1 million marks, and the builder provided the lacking funds. West Germany's Ministry for Food, Agriculture and Forestry assumed financing of operation of the underwater habitat.

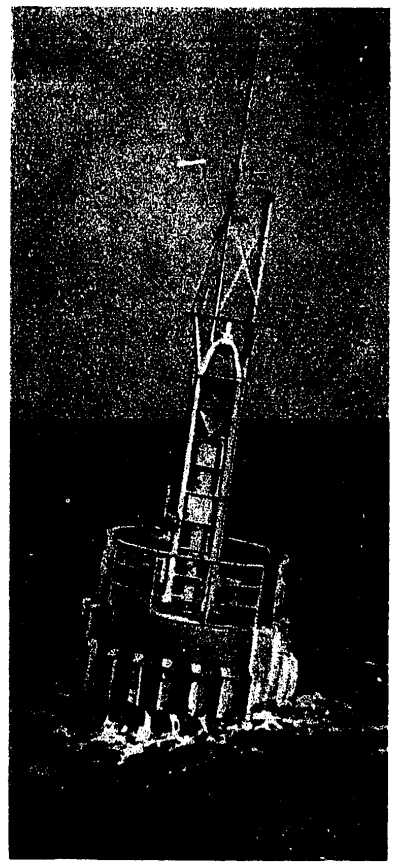
The total complex consisted of the undersea habitat proper, which was given the name "Helgoland," its power buoy, "Fuestchen," and a shore base with auxiliary equipment. Since the habitat was to be operated for a period of several years, and under conditions of the stormy North Sea, employment of surface support vessels was clearly inadvisable.

The habitat has a cylindrical pressure hull 2.5 meters in diameter and 9 meters in length. The hull rests on the seafloor on two lengthwise supports; the habitat submerges and surfaces by flooding the water ballast tanks or blowing them with compressed air. Full underwater displacement is 75 tons; the habitat weighs 16 tons on the bottom in working configuration.

A distinctive design feature of the "Helgoland" is increased structural strength of one of the two compartments. The compartment is capable of withstanding the external pressure of a 100-meter water column, while interior pressure can equal atmospheric. This permits the crew of the habitat to undergo decompression while on the seafloor, in the higher-strength hull compartment, and to surface in diving gear upon completion of decompression. This method of crew recovery was extensively employed during practical operation of the habitat.

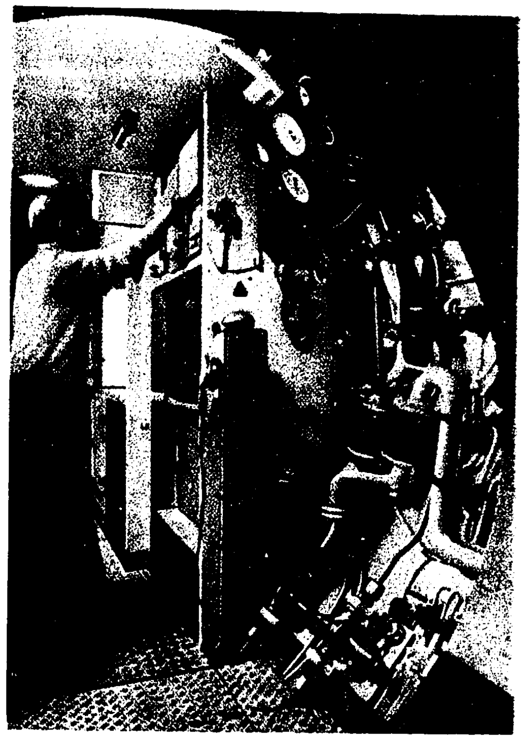
This undersea laboratory has one additional feature -- it can be hermetically joined to a one-person portable decompression chamber. The capability of "dry" docking between habitat and transfer chamber is an extremely valuable property, but in the case of the "Helgoland" this capability was only theoretical -- this method of crew recovery was not once employed by the aquanauts.

Electric power, compressed air, and fresh water were supplied to the habitat from the "Fuestchen" unmanned power buoy anchored above. This buoy is in the shape of a vertical cylinder 3 meters in diameter and displaces 16 tons. Contained inside the buoy's hull was a 15 kilowatt diesel-powered generator, two diesel-powered compressors, 14 tanks of breathing mixture component gases for the habitat crew, fuel tanks, and fresh-water tanks.



"Fuestchen" Power Buoy, From Which the "Helgoland" Undersea Habitat Receives Electric Power and Compressed Air.

Utilization of an unmanned surface support buoy made it possible greatly to reduce the number of auxiliary personnel. In 1969 only 17-18 persons participated in the habitat experiment: the coordinator (project supervisor), four professional divers (the qualifications of two of these corresponded to our category "expert diver"), one electrician and one maintenance mechanic, both diver-qualified, four amateur support divers, two doctor-physiologists, one diesel and compressor operator, who periodically serviced the support buoy, one storekeeper, and the powerboat diver tender crew members. Shore equipment included a decompression chamber and two Dreger high-pressure electric compressors.



Living Quarters of "Helgoland" Habitat. This Compartment Contains a Life-Support System and Air-Gas System Control Panel.

On 23 July 1969 the "Helgoland" habitat, with crew on board, was positioned on-site off Helgoland Island, 3 kilometers from the shore base. The sea depth is 21 meters at this site, water temperature averages approximately 12°C, the current runs at 1 meter per second, water clarity ranges from 0.5 to 5 meters, and tides run 2 meters. For a period of 22 days three biologist-aquanaut crews, relieving one another, conducted scientific investigations. The "Helgoland" research program called for study of plankton, ecology of invertebrates, as well as a live-fish tank experiment for raising fry in a natural marine environment.

After all three crews had completed their work, the habitat remained on the seafloor an additional 9 months. Finally it was surfaced in April 1970 and towed to a shipyard in Cuxhaven. Engineers and technicians from the Biological Institute and the Dreger Company worked for several months, readying the habitat and its support buoy for another mission. The administration of the Biological Institute, however, was unexpectedly faced with a financial problem: the federal government granted for conduct of the experiment a considerably smaller amount than requested.

Nevertheless the "Helgoland" habitat was ready for operation by the summer of 1971, and in August the habitat and its "Fuestchen" support buoy were transported to the Baltic coast and launched.

This time Eckernfoerde Bay was chosen as the immersion site. On 30 August 1971 the habitat was lowered to the seafloor, and a crew of four professional divers took up residence. During their three-week stay under water the crew performed thorough technical testing of the habitat. Because of appropriation cutbacks, however, the work volume was sharply reduced, and that season no oceanographic research proper was conducted.

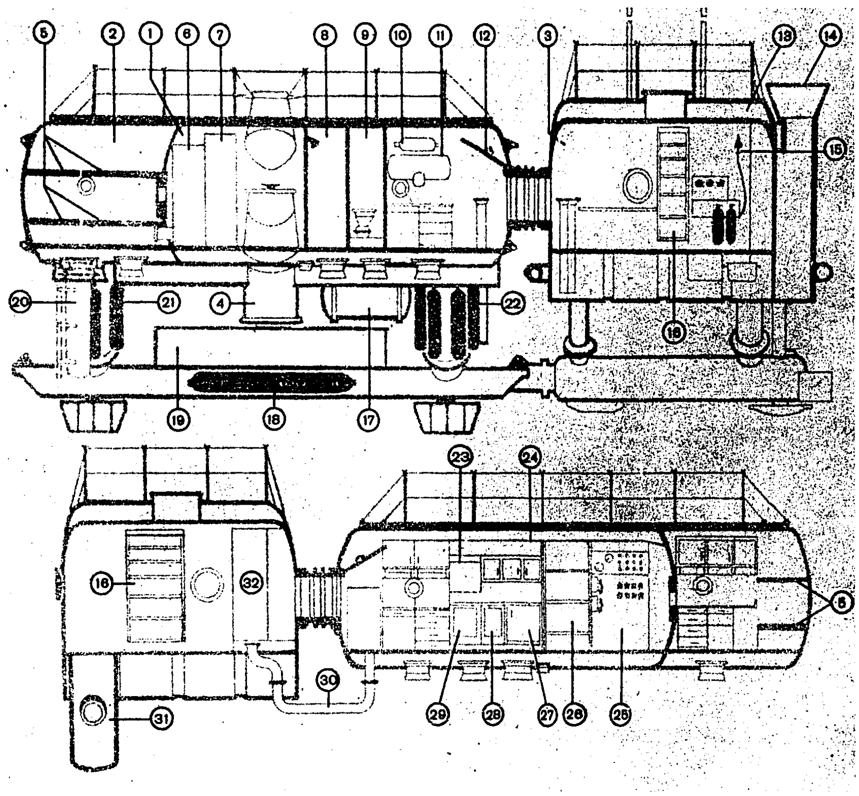
The organizational difficulties encountered by the Biological Institute forced the institute administration to find a new patron for the undersea laboratory. The Society for Utilization of Nuclear Energy in Shipbuilding and Navigation, which had been appointed by the federal government to coordinate work on development of marine technology in the FRG, became its new patron. The Society was to provide support services for the habitat, while the Biological Institute retained responsibility for carrying out the scientific research program.

Society engineers approached their task in an innovative manner. Evaluating habitat operating experience, they decided to increase useful in-hull space, adding an additional compartment. This new compartment was to serve as a diver compartment and gear locker.

The contract to design and build the additional compartment was granted to that same Dreger Company, and the compartment was delivered to the harbor on Helgoland Island at the beginning of summer 1973. Divers had soon joined the main compartment with the additional one, and following brief testing the habitat was ready to go to work.

In August 1973 the habitat was placed on the seafloor at a depth of 23 meters, 4 kilometers south of the Island of Helgoland. The first four-man crew took up residence on 16 August. This crew returned to the surface 19 days later. Subsequently two additional teams of aquanauts manned the habitat. The last crew returned to the surface on 1 October.

In the 1973 work season the aquanauts, in additional to technical and medical-physiological experiments, conducted observations of the life habits of invertebrates of commercial interest. This stage of the "Helgoland" program involved the participation of 11 U.S. observers, scientists and engineers. Their job was to determine the possibility of utilizing the "Helgoland" habitat for the conduct of investigations off the northeastern coast of the United States.



Schematic Longitudinal Section of "Helgoland" Undersea Habitat, Outfitted with Additional Diver Compartment.

Key:

1. "Wet compartment"
2. Decompression compartment
3. Additional compartment
4. Diver's exit well
5. Bunks
6. Power panel
7. Life-support system
8. Shower
9. Toilet
10. Oxygen metering
11. Water heater
12. Hatch
13. Buoyancy tank
14. Hopper
15. Shower
16. Shelves
17. Sludge collecting tank
18. Air tanks
19. Backup storage battery
20. One-man escape capsule
21. Nitrogen tanks
22. Oxygen tanks
23. Stove
24. Freshwater service tank
25. Air-gas system control panel
26. Test instruments

Key to Diagram on preceding page, cont'd:

27. Sink
28. Deep-cold refrigerator
29. Refrigerator
30. Main air connector line
31. Observation chamber
32. Drying cabinet

Diagram of Working Area Setup for "Helgoland" Undersea Habitat in 1969 Expedition Season

Key:

1. Habitat
2. Emergency shelter
3. Stores
4. Tender buoy
5. Sewage disposal
6. Rocky ridge
7. Tender buoy anchors

The "Helgoland" undersea habitat was launched once again in the summer of 1974. This time the agenda called for technical tests and training of crews prior to transporting the habitat and its tender buoy to the United States. A total of 30 engineers and oceanographers spent time on board the habitat, sited at a depth of 15 meters, in a period of slightly more than 3 months.

In the summer of 1975 the "Helgoland" habitat, its "Fuestchen" power buoy and auxiliary equipment were loaded on board the Polish freighter "Pomorze" in the port of Luebeck, to be transported to the United States. The expedition worked along the coast of Maine, engaged in a study of herring spawning.

The expedition was multinational in composition: in addition to Americans, participants included Germans and Poles.

U.S. Undersea Habitats

Experiments conducted with the "Sealab" and "Tektite" habitats, the successful month-long drift by the research submarine "Ben Franklin" in the waters of the Gulf Stream, plus a number of other experiments of this nature conducted at the end of the 1960's and beginning of the 1970's in the United States, considerably heightened interest by the U.S. scientific community in the problem of ocean research "from the inside." This in turn led to expansion of underwater research conducted in the United States. In 1971 the U.S. Government established, within the framework of the National Oceanic and Atmospheric Administration (NOAA), a special division for manned underwater equipment and undersea research. It was assigned coordination, development and implementation of various undersea research programs.

Projects in 1972 conducted under the division's general oversight included participation of eight manned research submarines and two undersea habitats: "Edalhab" and "Hydrolab."

Research volume in 1973 was somewhat reduced -- only three manned research submarines and two undersea habitats were operating: "Hydrolab" and "La Chalupa" (belonging to Puerto Rico).

During the years of its existence the division organized three major expeditions involving extended human habitation under water: "FLARE," "Hydrolab," and "PRINUL." All these expeditions were highly typical in their way.

The undersea habitat "Edalhab" and the support vessel "Lulu" took part in the "FLARE" expedition. The entire aggregate of equipment was highly mobile, but the habitat was totally dependent on the support vessel.

The "Hydrolab" program was based on an undersea habitat remaining at a single site for several years. This was a typical permanent undersea habitat.

The research conducted from the "La Chalupa" habitat for the "PRINUL" program was in its organization intermediate between the "FLARE" program (a mobile and non-self-contained habitat) and the "Hydrolab" program (a self-contained but permanent habitat).

The FLARE expedition. Experience with stationary undersea habitats indicated that, in spite of the promising aspects of this method of studying the ocean, the fact that a habitat cannot be quickly moved from one seafloor site to another considerably diminishes its effectiveness as a base for undersea research. In order to determine the degree to which the mobility of a habitat increases yield of scientific results, in January 1972 division personnel organized field studies, the program of which was based on employment of a mobile undersea habitat.

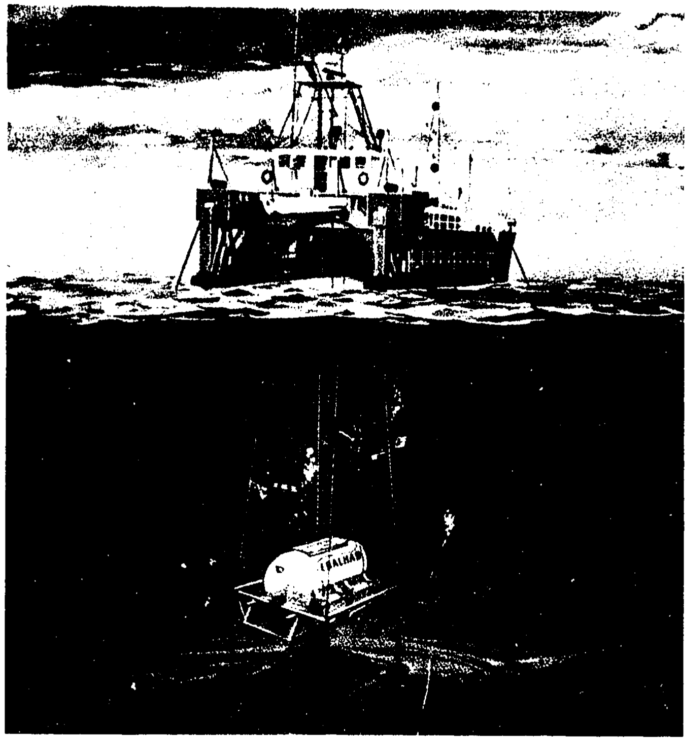


Diagram of Operations With the Edalhab Habitat in the FLARE Program. The Habitat Received All Requisite Supplies and Support Services From the Support Vessel "Lulu", Which Was Anchored Directly Overhead

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The planned expedition was code-named FLARE (an acronym of the words "Florida Aquanaut Research Expedition").

Endeavoring to organize research with "limited funds," division personnel decided to utilize already existing hardware -- a habitat and support vessel. Mobility was the principal requirement on this aggregate. After considering all possible combinations of habitats and support vessels available to the division, the program directors selected the University of New Hampshire's undersea habitat Edalhab and the catamaran "Lulu" -- tender for the research submarine "Alvin," which belonged to the Woods Hole Oceanographic Institution.

In the Edalhab-"Lulu" combination, the primary role was played by the support vessel. Its functions included transporting the habitat to the work site, lowering it to the seabed, supplying the habitat with electricity, air and water, crew decompression at the end of the mission, and bringing the habitat back to the surface.

The "Lulu" is a catamaran of about 500 tons displacement. The vessel is 30 meters in length, 14.5 meters in beam, and draws 2.7 meters. Its twin hulls are spaced 6 meters from one another and connected by strong structural arches and a deck. The vessel's speed is 6-7 knots.

There is an opening at the center of the catamaran deck, through which the habitat was lowered to the seabed and raised to the surface by the support vessel's winches. The hoist system's load capacity is 27 tons. Set up on the tender during habitat support activities were a decompression chamber, two electric-powered air compressors with a working pressure of 350 atmospheres, and a shallow-water diving station, which included scuba equipment and hose breathing apparatus. An inflatable rubber craft powered by an 18 horsepower outboard motor was employed as an auxiliary.

The vessel carried an 11-man crew; an additional 21-man team handled habitat operation and research activities.

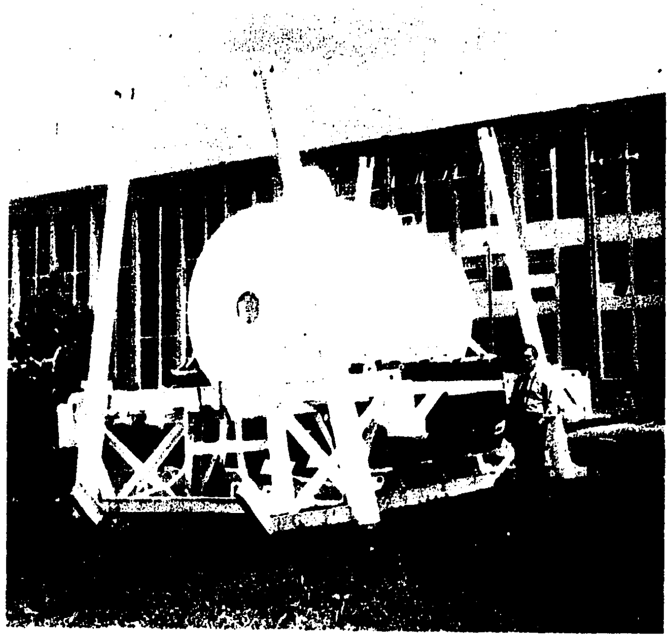
The Edalhab habitat was built by students and faculty of the Engineering Design Analysis Laboratory at the University of New Hampshire. Many components and assemblies were taken from retired and scrapped vessels, and therefore the habitat cost only $20,000.

Edalhab is the smallest of all existing undersea habitats. Its living quarters are housed in a cylinder 2.4 meters in diameter and 3.5 meters in length. A small viewing port is mounted in one of the end bulkheads. A diver exit well is located at the center of the compartment, and above it is a deck-exit well with an airtight hatch. The furnishings of the living quarters are simple -- two bunks and a folding table.

The habitat's hull is secured to a frame, which in turn can be raised on four supports to a height of 2.4 meters above the seafloor. Two weights of two tons each, suspended from the habitat, serve as anchor weights. The habitat also contains four water ballast tanks, used to adjust buoyancy.

Of course the support vesself "Lulu" assumed the task of providing the habitat's crew with whatever they could not provide themselves -- and due to the habitat's primitive design, it could provide practically nothing. The per-day cost of operating the "Lulu"-Edalhab complex was approximately $1,000.

The research program called for a series of seven habitat submergences off the Florida coast at depths of up to 13-14 meters, in a zone extending 40 miles north to south. The tasks of the habitat's crews included geological investigations, study of the natural history and ecology of coral reefs, and observations of the behavior of living organisms both at the level of basic and applied research.



Edalhab habitat at dockside at the Woods Hole Oceanographic Institution

The FLARE program was carried out in several stages. In January 1972 the "Lulu," carrying the 20-ton habitat in suspended position, headed out to the submergence location; by that evening the habitat was on the seafloor and the crew had proceeded with their work activities. After the first two crews had completed the first stage of the program, the habitat was hoisted on board the "Lulu," and the vessel proceeded to the next worksite, 22 miles to the north. The operation changed location one more time, and toward the end of the expedition the habitat and its support vessel returned to the area of the first submergence to perform a control series of experiments. The entire expedition ran approximately 100 days.

The Hydrolab program. The research program conducted with the hydrolab habitat is one of the most significant both in terms of volume of observations performed and duration of continuous and mishap-free operations. For several years now this habitat has been sited at a depth of 15 meters near the town of Freeport in the Bahamas. It stands at the edge of a coral reef, on a flat sandy bottom sparsely dotted with coral "bushes."

The Hydrolab is one of the smallest, simplest and cheapest undersea habitats. A horizontal cylindrical hull 2.4 meters in diameter and 4.8 meters in length is secured to four tubular supports 0.9 meter above a concrete base slab. The habitat is submerged to the seabed by pumping water into ballast chambers in the concrete base slab and into ballast tanks on the hull. It surfaces by blowing out the ballast tanks and chambers with compressed air.

The living quarters contain two bunks, two folding chairs, a folding table, and small drier modules. Two entrance wells lead into the living quarters. One -- the diving well -- comprises a vertical cylinder with an exterior and an interior hatch. The space between hatches is sufficient to airlock personnel into the laboratory compartment via the diving well if pressure in the compartment differs from outside pressure. The second entrance well is a tunnel passage designed to dock to the habitat a research submarine containing a diver compartment, such as the "Deep Diver." A flat viewing port 0.9 m in diameter is mounted in one of the end bulkheads. Through this port the observer can view a panorama of the nearby seabed. Several small ports provide side-viewing observation of the adjacent water area.

A distinctive feature of the design of the Hydrolab habitat is great hull strength, which makes it possible when necessary to maintain in the living quarters compartment, when the habitat is on the surface, a pressure equal to water pressure at the working depth, and at working depth to maintain in the compartment pressure equal to atmospheric. This capability expands the habitat's capabilities as a research equipment platform.

An unmanned tender buoy stands at anchor above the habitat. The buoy consists of a motorboat hull 6.9 meters in length, carrying a diesel generator, a compressor, a tank for fresh water, and a 1 cubic meter fuel tank. Electricity, air and water are delivered to the habitat through a cable-hose arrangement. A radio transmitter is provided for communication between habitat crew and support personnel. One of the crew members is on duty in the habitat at all times and maintains contact with the support services.

The "undersea habitat-power buoy" system, as is indicated by the operating experience of the Hydrolab complex, is reliable and highly economical to operate. However, the path of the design engineers of the Perry Oceanographics firm to arrive at this complex was long and thorny.

In the first version of the habitat, its hull was secured to the foundation base by cables. During the very first gale-force wind, the waves separated the hull from its base, and the habitat with its crew bobbed to the surface. Before going down a second time, the habitat hull was secured to the base by a double set of cables, but the very first gale-force winds ripped the connection apart. As a result it was necessary to secure the habitat hull to the base by four tubular supports, an arrangement which is still being used.

At the first stages of operation the habitat served as a test stand for new technical innovations. In 1969, for example, the habitat operated for 72 hours under water, while utilizing a block of hydrogen-oxygen fuel cells as power source. The process of docking a manned research submarine with the habitat was worked on in another series of experiments. This was the first experiment of its kind, and should be discussed in greater detail.

Usually if a crew member becomes ill the entire habitat must be raised to the surface, especially if the aquanaut's condition prevents him from transferring in diving gear to a diving bell lowered to the habitat. Such a method of personnel removal is inconvenient for two reasons. First of all, as a rule when the habitat surfaces the program of experimentation is interrupted and, secondly, it is not always possible for the habitat to surface immediately (either for technical reasons or due to surface weather conditions).

Obviously the most expedient mode of removal of sick or injured personnel is "dry" transport to a shipboard or shore decompression chamber with the aid of special transfer chambers which can dock with the habitat and establish an airtight docking seal. Prior to the experiments with the Hydrolab habitat, such "dry" docking was merely a dream on the part of habitat and support crews. The first attempt at such a docking was undertaken several years ago and occurred as follows. The research submarine "Shelf Diver" approached an undersea habitat and positioned itself hull against hull. The research submarine operator then carefully positioned the submarine onto a frame mounted on the habitat base, and positioned the craft so that the opening of the exit well from the diving compartment entered the coaming guides of the transfer tunnel of the habitat docking assembly. Then a member of the "Shelf Diver" crew manipulated a mechanical claw to seal the connection between the submarine's diving compartment and the habitat's connecting tunnel, equalized pressure in the diving compartment and tunnel and opened the hatch of the diving compartment well, establishing a transfer passage between habitat and submarine.

The research submarine "Shelf Diver" can be docked with a habitat not only when the breathing mixture pressure inside the habitat is equal to exterior pressure but also with normal atmospheric pressure inside the hull.

Following a series of brief submergences at various sites in Florida coastal waters, the Hydrolab habitat and its power bouy were sited 1 mile from Freeport harbor in the Bahamas. Perry Oceanographics announced that the habitat was available for rent to all interested parties for a moderate fee -- 250 dollars per day.

The habitat has had many visitors in recent years. Numerous filming teams have worked on board, and it has harbored vacationers, but for the most part the habitat has been used as a platform for oceanographic investigators and their scientific equipment.

In the 1972 and 1973 seasons the Hydrolab habitat was operated chiefly on contract and with funding from NOAA's Division for Manned Underwater Equipment and Undersea Research. The contract between the Division and the habitat's owner -- Perry Oceanographics, specified four submergences in May-June 1972 with the crew remaining under pressure for extended periods, plus four additional submergences running seven days each between July 1972 and June 1973.

The Hydrolab Undersea Habitat Has Served For Several Years Now as a Base for the Conduct of Oceanographic Investigations.

In 1973 the volume of investigations performed from the habitat tripled in comparison with preceding years, in particular by habitat utilization as a classroom for student oceanographers. Habitat crews did not lose a single working hour in the winter of 1972-73, in spite of the fact that approximately 20 percent of the time the surface swell prevented divers from going down, and 25 percent of the time wave heights reached 3.6 meters and it was possible but hazardous for divers to descend to the seafloor, while it was absolutely impossible to lower equipment down.

The aquanaut work schedule in the 1972-1973 seasons included a number of tasks. Biologists studied the state of "health" of the coral reef, distribution of plankton, the habits and dynamics of the coral reef fish populations, and the influence of sewage and oil on the living organisms of the reef communities. Bioacousticians recorded and identified fish sounds; oceanographers collected and interpreted data on the hydrologic parameters of seawater; hydrochemists studied the chemical composition of the water and its content of dissolved gases; physicists recorded cosmic radiations penetrating past the water surface.

The habitat was also used to study the physiological aspects of an extended stay by humans under elevated pressure, the habitability of an undersea habitat, as well as microbiological observations. On some missions the habitat was employed as a training and practice facility.

September 1944 marked 42 months of continuous operation of the Hydrolab habitat at sea. During this time 262 experiments were conducted with personnel spending several days in the underwater laboratory, while the total number of scientists and technicians serving on habitat crews reached 182. A total of 229 teams visited Hydrolab. Habitat activities were organized and financed by the Division for Manned Underwater Equipment and Undersea Research.

Operation of the Hydrolab undersea habitat continued in 1975-1976.

PRINUL -- Puerto Rico Underwater Laboratory. The activities of the PRINUL (acronym for Puerto Rico International Underwater Laboratory) occupy a special place in U.S. undersea research programs. Technically the facility is located outside the United States, but its operations are run by U.S. scientific and technical personnel and are financed chiefly by the United States.

The PRINUL underwater laboratory was organized under the aegis of Puerto Rico's Department of Natural Resources in 1971. Establishment of this facility pursued the following objectives: expansion of the volume of marine research in Puerto Rican waters; establishment of an underwater laboratory suitable for the conduct of underwater oceanographic investigations; student oceanographer training in undersea laboratories; familiarization of doctors with the specific features of diver activities under conditions of extended periods of time under pressure. But of course the principal emphasis was on conduct of oceanographic research proper, utilizing the underwater laboratory's equipment.

The Puerto Rican Underwater Research Corporation and the U.S. Marine Resources Development Foundation took part in establishment of the Laboratory. Selected as the Laboratory site was an area off Puerto Rico's southwestern coast. The Laboratory works in close cooperation with a number of U.S. organizations and government agencies, namely: the Department of Commerce, Department of the Interior, HEW, as well as the U.S. Navy, the National Academy of Sciences, the National Aeronautics and Space Administration, the U.S. Atomic Energy Commission, and the National Oceanic and Atmospheric Administration.

Structurally the Laboratory includes an equipment operation support service and a scientific team. The Laboratory's equipment includes the undersea habitat proper, diver shelters, a surface tender buoy, two powerboats, a diving station trailer, and two auxiliary service trailers.

The habitat and tender buoy were built to order for the Laboratory by Perry Oceanographics.

After it was launched, the habitat was given the name "La Chalupa." Built to state-of-the-art, this habitat is one of the most interesting designs at the present time, and it should be discussed in detail.

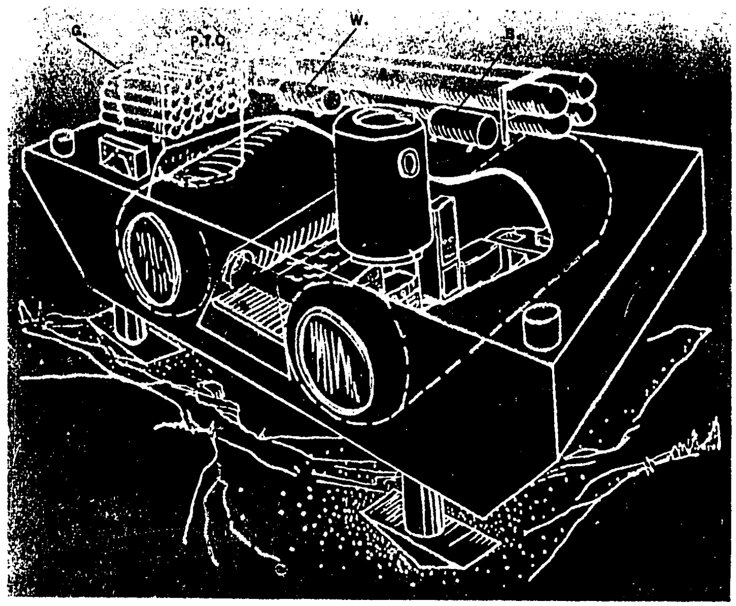
The "La Chalupa" habitat is designed to provide normal life and work support for a team of four aquanauts at a depth of up to 30 meters. It constitutes a towed barge, in the hull of which all habitat components are assembled. The habitat displaces 136 tons, has a hull length of 14.6 meters, is 6.1 meters wide, 3.25 meters high, with a 1.35 meter freeboard in surfaced cruising configuration.

When at working depth, the habitat hull stands on four pneumatic supports 0.61 m in diameter, which can be used to adjust the habitat's position relative to the seabed.

There are two pressure compartments within the hull (in the bow and aft sections), a working compartment between them, main water ballast tanks, water ballast tanks to hold the habitat against the seabed in working position, and permanent solid ballast. On the top deck there are four sets of hose breathing apparatus with 45 meters of hose, a rack of tanks with a working pressure of 140 atmospheres, containing an on-board supply of oxygen (85 m^3), nitrogen (85 m^3), and air (141 m^3), reduced to atmospheric pressure, a tank containing an emergency freshwater supply (227 liters), an emergency storage battery which can power the habitat's systems for 48 hours, and a coaming for docking a diving bell to the habitat.

The habitat's pressure compartments are in the shape of cylinders 2.4 meters in diameter and 6.1 meters in length. The forward pressure compartment is the living quarters, equipped with life-support systems, electricity and communications, with four bunks and laboratory work tables. Flat viewing ports 1.07 m in diameter are mounted in the end bulkheads. The compartment contains a hatch which leads to the work compartment and a hatch which leads to the habitat's top deck.

The habitat's after pressure compartment is set up as a control center. It contains the life-support systems monitoring and control equipment, electrical equipment and communications gear, as well as auxiliary equipment. This compartment also contains a viewing port 1.07 m in diameter and hatches leading into the work compartment and to the habitat's deck.



"La Chalupa" habitat -- one of the most modern undersea habitats operating at medium depths.

L.C. -- living compartment; C.C. -- control compartment; S.P. -- diving compartment; A. -- compressed air tank; W. -- emergency fresh water supply; B. -- emergency storage battery ; P.T.C. -- diving bell

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The pressure compartments can withstand an internal pressure of 3.5 atmospheres, which means that the crew can decompress at the surface. If it is impossible to surface the habitat, the crew can undergo decompression at working depth, utilizing the control compartments as a decompression chamber.

The work (diving) compartment, 2.7 meters in length and 6.1 meters in width, is situated between the living quarters compartment and control compartment. It contains diving gear, and divers enter the water from here. The work compartment can also be utilized as a shelter for the "Reef Hunter" two-man permeable-hull vehicle.

Diver work shelters have been set up on the seafloor in the vicinity of the habitat. These are transparent plexiglass hemispheres 1.2 m in diameter, filled with air and mounted on a steel rod frame. Their principal function is to provide the capability for communication between divers and with the habitat, but when necessary they can also serve as emergency shelters. Each such shelter contains a spare aqualung.

The surface buoy is designed to supply the undersea habitat with electric power, compressed air, water, and radio communications with the surface. The buoy hull is a refitted 11-meter fiberglass powerboat hull. The buoy compartments contain two 20 kilowatt diesel generators (main and backup), which supply electric power by cable to the habitat, a high-pressure diesel compressor, a low-pressure diesel compressor, and a refrigeration unit, which feeds cold water into the habitat's breathing mixture conditioning system. The buoy also contains a VHF radiotelephone communications system for communications between habitat and shore, wire communications equipment, a telemetry system, and a small computer for primary processing of scientific data and preparation of data for transmission to the shore base. The buoy contains a 3.8 ton capacity fuel tank and a 3.8 ton capacity fresh-water tank.

The buoy is anchored to the habitat. The anchor end serves at the same time as a support for the cable-hoses linking the buoy to the habitat. The habitat's land support facilities are housed in three trailers. This gives the land stations mobility and makes practically any coastal location accessible to investigation.

A diving station is housed in one of the trailers. It contains two high-pressure compressors for charging breathing air tanks, racks for storing diving gear, and a workbench for repairing gear. Housed in a second trailer is an electronic equipment servicing laboratory and a project command post equipped with radio communications and video recording gear; the duty officer station is located in this trailer. Housed in the third trailer are diver living quarters and a small medical aid station.

Additional equipment used in conjunction with the habitat are two motorboats and two outboard-powered inflatable rubber craft.

Two days prior to a scheduled habitat submergence, all equipment needed for performing the planned activities is loaded into its spaces, all habitat systems are thoroughly checked, and pressure in the living quarters compartment is raised to pressure at the working depth with the aid of pure nitrogen. The habitat is then towed to the submergence site, where three anchors have been placed on the seabed in advance. The habitat is secured to the anchors, and divers extend the habitat support and take water into the ballast tanks. Developing negative buoyancy, the habitat sinks to the seafloor. After this, two divers level the habitat with the aid of the supports, let water into the ballast tank which holds the habitat securely against the seabed, and connect the cable-hose from the tender buoy to the habitat's hull. Then the engineer servicing the habitat's systems blows out the work (diving) compartment with air, equalizes pressure in the living quarters compartments with outside pressure, and makes a final adjustment of the nitrogen-oxygen breathing mixture. Only after all these operations are completed is electric power fed to the habitat from the surface, and the crew proceeds to move in. It usually takes about one hour from the moment the habitat submerges to the moment the crew moves in.

After moving in, radio and TV communications are maintained around the clock with the habitat crew. Particular attention is focused on aquanaut activities outside the habitat, composition of the breathing mixture, and the results of the habitat systems status check, performed four times each day. All events taking place in the habitat are recorded in the ship's log. Two duty divers are available to the shore base at all times, ready at any moment to come to the crew's assistance. They also periodically inspect the tender buoy and the habitat itself.

Prior to surfacing, the aquanauts collect all equipment and go into the living quarters compartment, seal it and raise compartment pressure to 0.3 atm. Above the ambient water pressure, in order to make sure that the compartment is properly sealed. Then the shore base divers blow the water ballast tanks with compressed air, and the habitat rises to the surface. Once on the surface, the main ballast tanks are blown, and the habitat transitions to cruise configuration. After this the crew decompression process proper begins, with the control compartment utilized as decompression control station.

Laboratory activities are run on a commercial basis. Any scientist may take part in habitat missions. The cost of a 14-day training period is $ 700 per person, while the per-day cost of a stay in the undersea habitat is $ 230.

The habitat crew begins training and familiarization with habitat operation from 8 to 10 days prior to submerging. Training begins with classes in first aid and the basis of high-pressure physiology. Medical-physiological examination of the habitat crew is conducted in parallel, including general analyses of blood and urine, blood coagulation, and cardiovascular system functioning. Personnel then begin studying the rules and procedures of operating habitat equipment.

Crew general physical training consists of a series of dives, during which the crew selects a location for the habitat which corresponds to their scientific interests to the greatest degree. The aquanauts also undergo preparation for the performance of scientific investigations proper during the training period: they are familiarized with the equipment and work area, work on scientific investigation methods in field conditions, and receive background data requisite for the forthcoming investigations.

The Laboratory began performance of scientific research activities in September 1972. These programs can be divided into three groups: medical-physiological investigations, technical investigations, and oceanographic research.

Medical-physiological research involves chiefly two areas. The first involves investigations of bone necrosis phenomena which occur during disruptions of decompression procedures; these investigations are conducted with the aid of radiography. These studies are conducted under the aegis of the U.S. Department of Health and the U.S. Navy. The second area is development of decompression procedures under actual field conditions.

Experimental decompression procedures were developed by Ocean Systems Incorporated on contract with NOAA's Division for Manned Underwater Equipment and Undersea Research. The objective was to determine the maximum allowable depth to which a diver can descend from the "saturation" level, the time he can spend at that depth, and to set up suitable decompression tables for nitrogen-oxygen breathing mixtures. It was determined in the course of experiments employing shore-based pressure chamber facilities, for example, that a diver can descend to a depth of 52.5 meters from a "saturation" level of 30 meters for a period of 6 hours. This was tested by one of the habitat's crews in April-May 1973. Plans presently call for estimating the allowable time limit at a depth of 75 meters with a "saturation" level of 30 meters.

The program of medical-physiological studies also includes secondary tasks -- study of the specific features of spectral visibility under water, determination of the causes of outer ear infections in aquanauts and development of techniques of treating this affection.

Technical investigations involve chiefly testing of new equipment -- ultrasonic communication systems, telemetry systems for transmitting physiological data on the condition of an aquanaut working in the water, etc.

Oceanographic investigations in the first year of Laboratory activities were performed off Puerto Rico's west coast at depths of 18-21 meters. The principal goal of these investigations was a comprehensive study of the ecology of coral reefs and determination of characteristic parameters which would make it possible to establish space and time ecological relations and to establish a methodology of rapid evaluation of these relations in the future. Depending on the crew assignments, the habitat submergence site would move around within the limit of several miles. This substantially increased the effectiveness of the investigations being performed.

Immediately prior to completing decompression, the aquanaut team would present a brief report on investigations conducted, which would be discussed at a seminar with the participation of the members of the preceding and following teams. This practice enables subsequent teams to formulate their assisgnments more precisely.

Chapter 2. OCEANOGRAPHERS UNDER WATER

Advantages and Specific Features

In underwater research practice today, either habitats with normal atmospheric pressure in the compartments or habitats all compartments of which are under elevated pressure are being employed. However, conditions which permit extended investigator work duration in the water are clearly preferable. For example, during operation of the Hydrolab undersea habitat, which permits operation under both conditions, only 10 percent of the total number of submergences were conducted with normal atmospheric pressure in the compartments. In the remaining 90 percent of the missions, pressure in the habitat living quarters was equalized to external water pressure.

Evidently such a decisive preference for undersea habitats with elevated pressure in the compartments is due to the fact that in this case a capability for divers to work in the water in direct contact with the investigated object is combined with the capability to place on board the habitat a substantial amount of stationary analytical and electronic equipment. This more closely approximates undersea investigations and experiments to the conditions of on-land field research.

The annual volume of work performed out of undersea habitats has today stabilized at approximately 800 man-days per year. Table 1 lists the main areas of research performed in 1974 on the basis of undersea habitats and the volume of work performed in each specific instance.

We should note that a portion of the presented data was obtained indirectly; on the whole, however, the table reflects fairly completely the overall picture of scientific investigations.

Before proceeding with an analysis of the scientific programs conducted out of undersea habitats, we must stress that the habitat per se is a secondary research device: it provides the capability to conduct scientific investigations and to obtain scientific results, but the habitat proper is neither the investigation nor the result.

Table 1. Nature and Volume of Scientific Investigations (Man-Days) Performed out of Undersea Habitats, 1963-1974

Experiment	Hydro-physics	Hydro-chemistry	Geology	Biology (Ecosystems)	Hydro-bio-acoustics	Nuclear Physics	Mari-culture	Environment	Installation of Equipment	Underwater Technical Work	Total
Precontinent-2	–	–	–	82	–	–	–	–	–	–	82
Precontinent-3	20	–	20	20	–	–	–	–	–	60	120
Sealab II	40	–	40	80	–	–	–	–	110	–	270
Tektite I	–	–	90	150	–	–	–	–	–	–	240
Chernomor-68	60	–	20	20	–	–	–	–	–	–	100
Sadko-2	4	–	4	–	–	–	–	–	–	4	12
Chernomor-69	36	–	84	–	–	–	–	–	–	–	120
Helgoland-69	–	–	15	42	–	–	15	–	–	–	72
Sadko-3	14	–	14	7	7	–	–	–	–	–	42
Tektite II	–	135	100	556	50	–	–	50	–	–	891
Chernomor-71	100	–	100	32	–	–	–	–	–	–	232
Hydrolab-71	–	–	–	–	–	–	18	–	–	–	18
Hydrolab-72	–	142	21	–	–	–	–	–	–	–	278
Edalhab	–	–	18	115	–	–	27	–	–	–	111
Chernomor-72	85	–	80	40	–	–	–	–	–	10	215
La Chalupa	14	–	99	340	–	18	–	–	–	63	534
Chernomor-73	42	14	–	14	–	–	–	–	–	–	70
Hydrolab-73	–	69	–	138	–	33	–	42	–	–	282
Helgoland-73	–	–	–	184	–	–	–	–	–	–	184
Chernomor-74	23	12	23	23	–	–	–	–	–	23	104
Total volume of work activities	438	372	728	1909	57	51	60	92	110	160	3977
Relative volume of work activities (%)	11	9.4	18.3	48	1.4	1.3	1.5	2.3	2.8	4.0	100

There is one more distinctive feature -- the multiple-level character of undersea research.

More than 100 different investigations and experiments in the most diversified scientific disciplines have been performed on the basis of undersea habitats just in the last three or four years, and it is impossible for practical purposes to present a complete description of these activities in a single volume. Therefore we shall henceforth, after a general analysis of Table 1, discuss only the most typical areas of research investigation.

These in turn include hydrobiological investigations (48 percent of all research activities), followed by hydrogeological (18.3 percent), hydrophysical (11 percent), and hydrochemical (9.4 percent) investigations.

One can assume that the above distribution of volume of research investigation was determined primarily by the direct contribution of the human factor, namely diver labor, to a given category of research activity. Indeed, at the present stage the most "contemplative" science is biology, and the least is hydrophysics, including hydrooptics.

Thus biology, geology, hydrophysics and hydrochemistry are those basic areas of scientific study receiving the most attention on the part of the habitat aquanaut team members.

The Living Sea

As Table 1 indicates, biological research was the most actively conducted from undersea habitats. Observations and experiments are divided into two groups: basic, that is, academic research, and study of problems of applied biology.

Basic research covers practically all fundamental areas of biology. Aquanauts have studied the composition and distribution of microflora and plankton, ocean primary productivity and metabolism of individual specimens and communities, distribution of living organisms on the seafloor and within the water mass, specific features of the diet of marine animals, their behavioral reactions in various situations, and exchange of acoustic signals.

Investigations in the area of applied biology were directed toward solving chiefly the two most critical problems: pollution of the sea by the waste products of human activities, and establishment of controlled undersea mariculture operations.

Conducting biological research, aquanauts utilized the entire arsenal of technical means available to the investigator, from highly complex electronic measuring systems to simple hand plankton nets.

Basic biological research. As a rule the first activity of habitat teams whose work schedule includes biological research is study of the spatial distribution of living organisms around the habitat site. The method of performing investigations of this kind has been fairly thoroughly worked out by scientists diving from the surface with aqualungs, and aquanauts operating out of an undersea habitat have been successfully employing this methodology. It is based on employment of linear transects. Utilizing the unique biological map obtained with this method, subsequent teams of investigators can properly gain their bearings on the seafloor when selecting areas for conduct of scheduled experiments. The activities of the first crew of the Sealab II habitat are fairly indicative in this regard.

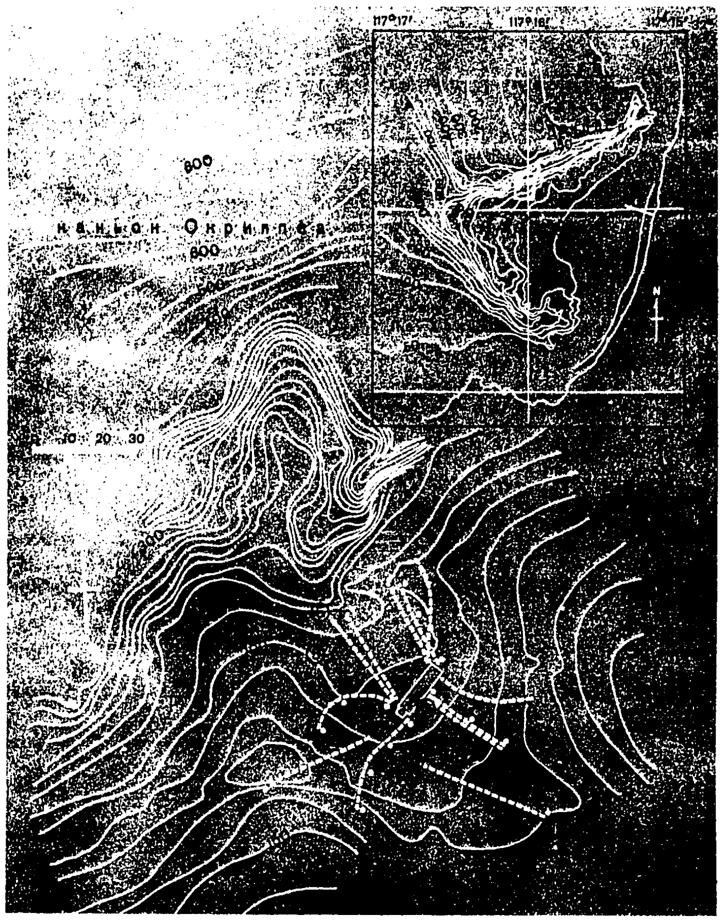
The aquanauts careful surveyed on the basis of transects the seafloor in the area around the habitat. Moving in a selected direction, they would either make a direct count of the population density of the seafloor surface with the aid of grid squares of 1 square meter, or they would take with a manual sampler soil samples 35 cm^2 in area and 5 cm thick for subsequent examination aboard the habitat. In some cases bottom mapping was performed prior to placing the habitat on the seafloor, in order to choose a submergence site. In preparing for experiments with the Hydrolab habitat, the seabed around the proposed submergence site was subdivided into sections. Section sides parallel to the coast were selected as base sides. Three lines -- transects -- each approximately 100 meters in length, running from a depth of 13.5 meters to a depth of 27 meters, were laid out through the center of a base side 800 meters in length and along its ends, perpendicular to the shore. At a depth of 27 meters each zone was closed by a second base line. Divers, moving along the transects, photographed the seafloor and took soil samples and coral specimens. After the survey materials were processed, a final determination was made of the habitat submergence location.

The seafloor biological mapping technique employed by the aquanauts of the PRINUL program appears to be the most sophisticated. The first team to man the habitat, in addition to other tasks, was to prepare a map of seafloor relief and distribution of seabed communities along the seafloor surface.

The aquanauts prepared four guidelines, each 6 mm in thick and 180 meters long, and laid them out according to the cardinal compass points, employing a hand compass, so as to form a square with the habitat in the middle. The guidelines were marked in advance in 10-meter intervals.

At each marked point on the transect line the aquanauts measured the depth of the seabed with a hand depth gauge and described the biological community at this point on the reef, assigning it to one of six types. In areas where there was a particular diversity in composition of flora and fauna, the survey point interval was reduced to 1.8 m.

These data would be plotted, and by the end of the work tour the aquanauts had produced a detailed contour map showing distribution of biological communities and seabed relief covering an area of 23,000 m^2. The aquanauts performed a photographic survey at nodal points with a particularly complex configuration of biological communities or topography.



Sealab II Habitat Siting Location

Key:

1. Transformer
2. Diving bell
3. "Benthic" underwater "weather station"
4. Fish enclosure
5. Hydrologic stations

dashed line -- Transects
dots -- Sediment sample collection point
horizontal scale -- in meters
depth scale -- in feet

The seabed map made by the first team of aquanauts became the basis for work activities of the next eight habitat teams.

After aquanauts have recorded a general picture of the distribution of living organisms and features of bottom topography around the habitat, they select a target of further investigation, in conformity with the basic objectives of the work program.

The bulk of basic biological research performed on the basis of undersea habitats has been accomplished by American aquanauts working in reef areas (this is understandable, for tropical waters offer an extremely fertile ground for biologists. Less attention was devoted to biological investigations in the "Chernomor" program, which is also understandable -- the waters of the Black Sea in which the aquanauts of this program worked are not so abundant with life and offer far less visibility than tropical waters).

The results of the reef studies performed by aquanaut participants in U.S. programs and the method of their conduct merit a more detailed discussion.

The reef with the living organisms inhabiting it -- fish, crustaceans, mollusks, etc -- is a complex world, full of interweaving relationships between individuals and species. A reef is similar to an independent organism, all parts of which function amazingly harmoniously and in an interrelated manner. Each species within the community of reef dwellers has its own "ration." Certain fish species feed only on fish, while others feed on worms and seaweed. One group of fish species feeds only on sand, while another feeds on the rocky portions of the reef. Some fish employ symbiotic relations -- for example, they feed on parasites which live on other fish. On the whole a reef is a self-regulating self-supporting world. And the foundation of this entire living microcosm is the coral reef itself, an organism which serves as a shelter, source of food, and symbiotic partner to myriad species of fish and marine algae.

One can comprehend these intricately interweaving, interlinking relationships and determine whether this amazing "organism" -- the coral reef biological community -- is healthy or sick only by means of extended, detailed observation.

The aquanauts of the Tektite program selected for detailed study an isolated reef of triangular shape, while the aquanauts of the FLARE program selected a dome-shaped coral reef. Both selected reefs were separated from neighboring reefs by a sand strip.

The first stage in the study of such isolated biological communities usually consists in determining the composition and size of the populations contained in a biological community. As a rule this work is performed by two aquanauts, who make a visual count and classification of individuals. If the area of the target reef is comparatively large, the count is conducted by sections. Both observers make several repeat counts until the results of their calculations agree.

The described method of determining composition and size of populations is simple and fairly effective, although it requires a large volume of diving work. It is an extremely laborious task to make a count of fish which are swimming back and forth. The job is no easier with "sedentary" fish: they retreat into natural shelters, and it is very difficult to spot them in these retreats.

The Tektite aquanauts, having completed their reef biological community population composition and size count, determined that permanent reef dwellers included approximately 53 species of fish, plus an additional 22 "visitor" species.

A control rotenone sampling was performed on the reef following the visual count. This sampling consists essentially in the following: a special poison which affects only fish is introduced into the water washing the reef. The experience of previous studies indicated that a two-time or three-time application of rotenone at an interval of several hours kills 85-95 percent of the fish on the reef. A count of the dead fish gives a more accurate picture of the fish inhabiting the reef than a visual count of live fish. The very nature of the rotenone test, however, makes its mass application out of the question: it kills the fish. Therefore rotenone is rarely utilized, and then only for verification purposes.

A rotenone test of a coral reef on which aquanauts had previously made a visual count showed that an additional seven species of fish which had not been counted by the aquanauts lived hidden within the reef, although the aquanauts had very thoroughly inspected every nook and cranny in the reef. The number of fish of six other species proved to be larger following the rotenone test than with the visual count, while 16 other species of fish were present in fewer numbers. And finally, the 22 visitor species spotted visually failed to turn up in the rotenone test. Evidently they had been able to escape from the reef upon first becoming aware of the poison.

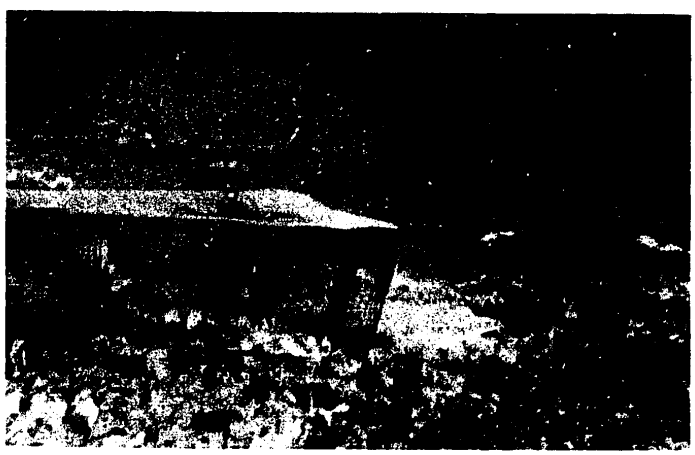
The next natural step in biological observations of seabed communities is study of the dynamics of populations taking account of habitation range, food competition, symbiotic relationships, and reactions of fish to external stimuli.

Aquanauts sought to determine specifically on what various fish species feed and the feeding activity of fish over the 24-hour cycle. Usually they would select the most "typical" reef in the vicinity of the habitat for studying fish feeding habits.

The Tektite aquanauts working in May readied in advance the field of activity for their colleagues, the biologists who would be coming down in June. In May two 180 meter transects were laid out from the habitat, cleaving the reef in two directions. One lay at depths of from 12.4 to 18.7

meters, and the other -- at depths from 17.3 to 21.5 meters. Along these transects the aquanauts distributed several mesh-covered frames measuring 1.35 x 0.6 x 0.45m with 1.3 cm^2 mesh. Those areas of seafloor under the frames, protected from large fish, would serve as control areas. In July a team which included biologist Sylvia Earl, an expert in fish feeding habits, descended to the habitat. During a two-week stay in the habitat she spent 40 hours in an aqualung and 46 hours in a closed-cycle scuba unit outside the habitat, at depths of from 10 to 24 meters. On a plastic sheet the biologist jotted down data on distribution of marine algae in the target section of reef, on the behavior of individual fish and mixed groups. She made many interesting observations in the two weeks.

A control inspection of the mesh-covered frames which protected marine algae from foraging fish indicated that within a radius of 60 meters around the reef marine algae under the protected frames, where fish could not eat them, grew considerably more rapidly than on unprotected spots. It was precisely the active feeding habits of plant-eating fish which explained the strange paucity of plants on the reef itself and a total absence of plants on the sandy seafloor around the reef.

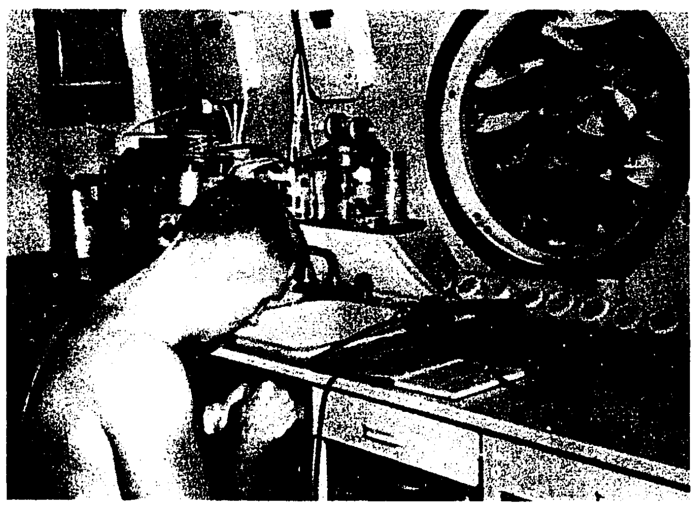


Tektite program biologists studied the influence of fish on algae growth on the reef, comparing the growth rate under a protective box of fine mesh and on unprotected spots.

Carefully observing the reef and its inhabitants, Earl counted 35 species of fish which feed on algae. During trips onto the reef she collected a herbarium of 154 species of marine algae, 26 of which had never before been recorded in the Virgin Islands.

Establishing the locations of most active fish feeding, Earl painstakingly collected all the algae growing on eight of these spots. Back in the habitat she sorted them by species and bound the algae of each species into bundles. She then tied a lead weight to each bundle and placed the entire collection in rows on the seafloor by the reef. Fish would approach and feed on algae of that species which was most to their taste. Observing who was feeding on what, Earl established the individual tastes of each species.

This is not the only method, however, of determining what fish feed on what. Light shining at night through the viewing ports of an undersea habitat attracts zooplankton. Fish feed on the plankton before the scientists' very eyes, while predators prey on the smaller fish. All this is taking place literally a few meters from the viewing ports, and the biologist observing from the habitat sees this picture in detail.



Light shining through the viewing ports of undersea habitats invariably attracts denizens of the sea.

Aquanauts have frequently speared fish and brought them back to the habitat to cut them open for analysis of the contents of their intestines. This has made it possible in many instances to detail the "menu" of small and large fish. Sylvia Earl noted that some fish species form stable mixed groups which come to graze on the reef, like herds of domestic livestock.

The majority of fish which feed on algae live either on or close to the reef, never moving more than 30 meters away from the reef. Occasionally fish were encountered, however, which fed on algae 60 meters or more away from the reef. For the most part it is small fish less than 10 centimeters in length which feed far from the reef. This is apparently due to the fact that in case of a predator attack, by a barracuda, for example, the small fish can take refuge among the algae, while it is difficult for large fish to hide.

A special series of experiments was performed by one of the Tektite program teams, for the purpose of determining what evokes a flight and self-preservation reaction in fish. They employed moving models for this purpose. In the process of the experiment they varied the size, shape and color of the models, as well as their rate of closing with the subject fish.

Sealab II habitat aquanaut studies the stomach contents of a fish specimen

The aquanauts employed models of three different shapes, cut out of plastic sheet: round, elliptical, and square. Models of each shape came in three sizes: 100, 200 and 400 cm^2. This series of models was white and intended for studying the reaction of fish to the shape and size of the models.

Models of a second group, made of opaque plastic of different colors, were in the shape of an ellipse and were colored black, red, silver, yellow, and white. One of the models was fashioned of transparent plexiglass, and one was in the form of a lattice ellipse with slots spaced at 2 centimeters.

It was suggested that on the basis of the reaction of fish to these models, which could not be seen in the water, one could judge their reaction to vibration caused by a body moving in the water.

The path of movement of the models was determined by guide threads; rate of movement could be varied from 0.3 to 2 m/s. Fish reaction was recorded by a remote-controlled motion picture camera mounted on a tripod on the seabed. The entire system would be activated when a school of fish containing 10-100 individuals approached the experiment setup. Mathematical processing of the photographic record enabled the scientists to draw a number of conclusions on fish reactions.

First of all, they failed to detect a substantial difference in fish reaction to a transparent and opaque model. Evidently fish react to water vibration caused by the moving model. They "fled" differently, however, from dark and light-colored models, meaning that they are not indifferent to color. On the whole, however, fish reacted more vigorously to a model's rate of movement than to its other characteristics.

There exist symbiotic relationships between many species of reef fish. Very indicative in this regard is the relationship between a grooming-fish and its "clientele."

As we know, this symbiotic relationship consists in the fact that the grooming-fish removes parasites from the gills, fins and scales of other fish. Such symbiotic relationships are known to exist with fish found in the Atlantic, Pacific, and bodies of fresh water. As regards fish inhabiting Caribbean reefs, the existence of such symbiotic relationships among them was placed in doubt, since it was believed that reef fish are infested with parasites only to a small degree.

Aquanauts of the PRINUL program devoted two weeks to a study of reef fish cleaning symbiosis. Proceeding along the transect guide line, the aquanauts marked on the map the summits of all reefs with a diameter of greater than 0.3 m. They also marked on the map the diameter of the reef summit and the presence of a "cleaning station" on it. A count indicated that grooming fishes inhabit 19 percent of the reef top and that the size of reef tops containing "cleaning stations" ranges from 0.3 to 1.2 m, averaging 0.69 m. Marking the "cleaning stations" with small buoys, the aquanauts determined that they do not change location -- the grooming-fish received "patients" at quite specific sites. There was an unexpectedly large number of such locations -- one every 8 m^2.

The overall density of "cleaning stations" in the study area turned out to be from one to two orders of magnitude greater than in the tropical zone of the Pacific. In order to determine how this fact tied in with the total quantity of exoparasites on reef fish, the aquanauts speargunned several fish for inspection. Each speared fish was immediately placed into a plastic bag, and later the fish's gills, fins, scales and body were examined under the microscope.

The study determined that fish infestation with exoparasites is unusually high, although in general there were few large exoparasites in the examined specimens. Evidently they were lacking due to the activities of the grooming fish. Therefore the scientists concluded that the grooming symbiosis is extremely important for the overall coral reef ecosystem.

Highly interesting results were obtained by aquanauts engaged in bioacoustic studies.

One of the first efforts in this area was a program of experiments by aquanauts of the "Sadko" program, conducted in 1969. The aquanauts employed a pen containing subject fish. The pen consisted of a net stretched over a frame, at the center of which the habitat was located. The volume of water encompassed by the pen totaled 350 m^3. Four hydrophones were placed inside the pen; the space inside the pen could be seen through the habitat viewing port, and this space could be motion-picture photographed. The hydrophone signals were recorded on magnetic tape in the habitat. By comparing the fish behavior recorded on film and the tape-recorded sounds, the aquanauts were able to identify the "voices" of certain fish.

A somewhat more ambitious program of bioacoustic observations was conducted by a team of biologists from the University of Texas, who worked for several years in succession on the Tektite, Hydrolab, and PRINUL programs.

These scientists elucidated the answers to a number of questions, including the following: what variations occur during a 24-hour cycle in the loudness and frequency characteristics of sounds emitted by fish? What fish emits what sound? What causes particular fish "talkativeness"? In addition the biologists were interested in the relationship between the acoustic signals emitted by reef fish and their behavior. And finally, they wished to make a comparative evaluation of the method of studying marine bioacoustics from undersea habitats and by diving from the surface with scuba gear.

Tektite aquanauts (1970) employed two sets of equipment -- mobile and stationary -- to record sounds. The mobile unit consisted of a cassette tape recorder in a watertight case and an underwater motion picture camera. Aquanauts would carry the portable recording unit to one of 17 preselected stations in the vicinity of the habitat and would observe fish behavior. At what in their opinion were appropriate moments they would switch on either the tape recorder alone or the tape recorder and the camera, synchronously recording both sounds and fish behavior.

The stationary unit was kept in the habitat. It consisted of a portable stereo tape recorder and two hydrophones connected to it by cables, each of which was 150 meters in length. Both hydrophones of the stationary listening system were set up on the reef near the laboratory in such a manner that one was visible through the viewing port in the diving compartment. The aquanauts conducted a series of very interesting observations through this viewing port.

The habitat team employed breathing apparatus of various types for work in the water. While observing fish the aquanauts noted that the air bubbles escaping from the aqualung into the water frightened the fish, causing them to "quiet down" -- the intensity of the sounds emitted by the fish would drop off sharply. At the same time the practically noiseless respirators -- closed-cycle breathing units -- did not attract the attention of the fish, and they permitted the scientists to approach much closer.

The magnetic tapes were processed later on shore, with the aid of frequency spectrum analyzers. Phonograms of the recorded sounds were plotted, from which the scientists were able to isolate several types of "standard" sounds emitted by the fish. The biologists were able to divide them into two groups -- sounds comprising the general acoustic background -- "crackling," "clicking," the sound of frying bacon, and sounds with a specific function -- "cooing," "drumroll," and "smacking." Spectrograms in "frequency-time" coordinates were plotted for all these sounds. Scientists were able to identify some of the sounds.

On the whole the aquanauts learned as a result of the 20-day study that the basic frequency range of sounds emitted by fish extends to 6 kHz, with the acoustic energy maximum emitted at frequencies of 3.5-5.5 kHz. Some fish, however, "talk" at frequencies of 100-600 Hz.

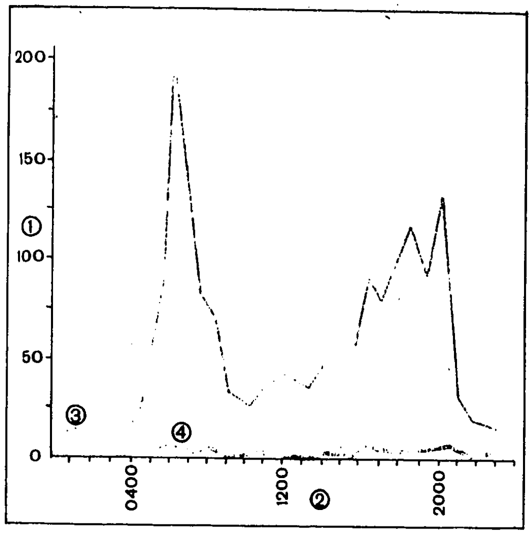
For some sounds, such as croaking, a clearly-marked daily cycle was established, while periodicity was not noted for others, such as clicking.

Many sounds were correlated with the behavior of fish, such as the squeal emitted by the parrot fish during feeding, but a great many other sounds have not yet been tied in with fish behavior. If sufficient material in this area is amassed, however, acoustic observation will become an effective means of studying fish behavior.

In the following year, 1971, for a period of 7 days aquanauts of the Hydrolab habitat, sited at a depth of 14.7 meters, carried out a similar program of investigations. The equipment and method of investigation were the same as in 1970. On the whole the results of this study confirmed and added to the materials collected by the Tektite teams.

Aquanauts conducted most of their observations at dawn and dusk, when fish would emerge from their grottoes to feed. These moments are described as "twilight" bursts of acoustical activity.

The aquanauts were able to establish that the level of acoustic signals directly corresponds to vigorousness of fish behavior: during the day the level is high, while at night it is low. The presence or absence of sounds on the reef unequivocally indicates the presence or absence of fish at this location. The relationship between fish acoustical exchange, sunrise, sunset and twilight in the area of the Bahamas where the Hydrolab habitat was sited is the same as at the Virgin Islands location where the Tektite habitat was operating.



Graph of intensity of fish "conversations" on a reef over a 24-hour period. Two bursts of fish acoustic activity -- in the morning and evening -- are clearly identifiable.

Key:

1. Quantity of sounds emitted in a period of 5 minutes
2. Local time
3. Individual "claps"
4. Series of "claps"

Hydrolab habitat aquanauts made several additional interesting observations. They established that parrot fish emit two types of sound during feeding, depending on their age: younger fish "squeak," while older fish "crunch." The aquanauts established experimentally that with each "crunch" a fish swallows 0.3 gram of limestone material (coral, for example). Comparing this quantity with the total number of "crunches" recorded on the reef during a 24-hour period, the aquanauts calculated that in a year's time 1,050 kg of material is processed in an area of 1 hectare at that location. This figure, obtained on the basis of analysis of sounds emitted by parrot fish during feeding compares fairly well with another quantity -- 600 kg, obtained from analysis of the contents of the intestines of parrot fish inhabiting "a typical Bermuda reef." The similarity of these results indicates that passive acoustic monitoring of reefs can greatly assist in determining the feeding habits of parrot fish.

Bioacoustical studies were continued in May 1973. This time the study focused on squirrel fish (Holocentridae). Aquanauts studied diurnal variations in sounds emitted by fish, in the hope of isolating defense and attack sounds as well as the relationship between sounds emitted by a fish at night and its behavior.

Just as the Tektite aquanauts, the Hydrolab aquanauts employed both aqualungs and almost noiseless respirators. And once again the scientists saw that fish "quiet down" in the presence of the sounds of a working aqualung.

The principal indicator of the health of coral reefs is the intensity of metabolic processes taking place in it. In the course of numerous studies of the metabolism of seafloor organisms and communities, including coral reefs, a certain method was developed, which was successfully employed by the aquanauts of the Hydrolab, FLARE, PRINUL, and Tektite II programs.

This method is based on employment of a seafloor respirometer. It comprises a transparent plexiglass hemisphere from 17 to 130 cm in diameter, with a flange 5 cm wide along the lower edge. The hemisphere is placed on the seafloor above the object of interest and its edges are sealed, to prevent exchange of water under the hemisphere with the water around it.

The hemisphere contains a water circulation system. The system consists of hoses through which water is drawn off from under the hemisphere and returned, a ventilation pump, a sensor indicating dissolved oxygen content in the water under the hemisphere, and a sensor recorder.

The ventilation pump is switched on either by hand or by the dissolved oxygen content sensor -- when oxygen content in the water under the hemisphere approaches the minimum allowable. The pump forces fresh water under the hemisphere, while excess pumped-in water is removed through a ventilation valve (which is normally in the closed position).

The above-described seafloor respirometer enables scientists to study the metabolism of individuals and communities not only in actual conditions but also in a number of artificial situations: restricted illumination, oxygen starvation, and introduction of various impurities into the water surrounding the organism. This makes it possible to determine environment parameters which are critical for living organisms, and consequently to predict the state of "health" of seafloor living organisms, according to the dissolved oxygen content in the water, for example. It was established, for example, that for coral reef inhabitants around Puerto Rico critical oxygen content in the water is 53 percent of the saturation figure. It was also established that the level of oxygen absorption by living organisms increases sharply immediately after sunset, subsequently drops and stabilizes at that level until dawn.

Parallel with study of the metabolism of coral reef communities, aquanauts studied primary productivity of the water mass over the reef and bottom sediments.

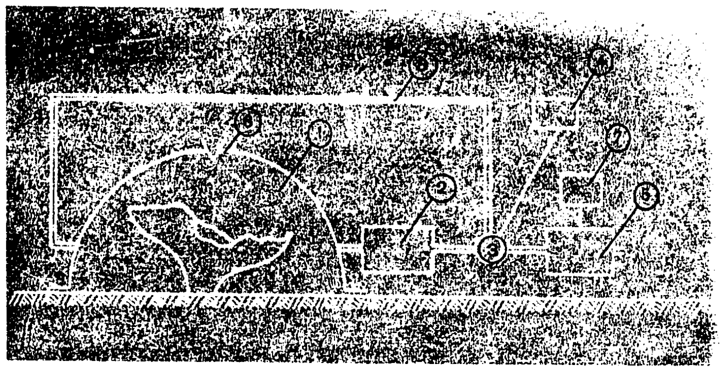


Diagram of Seafloor Respirometer

Key:
1. Hemispherical metabolism chamber
2. Circulation pump
3. Devices sensing content of dissolved oxygen in water
4. Dissolved oxygen content recorder
5. Ventilation pump
6. Ventilation valve
7. Ventilation pump switch-on mechanism
8. Supply and discharge pipes

Particular attention was focused on study of seabed primary productivity, since this had never been thoroughly investigated.

Hydrolab aquanauts utilized for this purpose a plexiglass chamber 3.5 cm in diameter, into which a sample of sediments taken at the base of the reef would be placed.

Five pairs of chambers with samples would be placed at levels of 18, 20, 22, 24, and 26 meters, and the isotope carbon 14, contained in the compound $NaHC^{14}O_3$, would be placed in the water in the chamber above the sample. Then one of the two chambers at each level would be left in the light, while the other would be shaded. At four-hour intervals after the experiment began, the aquanauts would gather up the samples and determine the degree of decrease in content of dissolved oxygen in the water above the sample and the quantity of the isotope C^{14} bound in the sample.

Practically every biological research program included study of the distribution of plankton in the sea.

The simplest plankton collection device used by aquanauts is a plankton hand net of fine-mesh fabric (mesh diameter 300 microns). The net is shaped like a cone with a water scoop diameter of 35.7 cm, which provides a capture area of 0.1 m^2. A ring 5 cm in diameter is attached to the point of the cone; attached to it is a removable PVC cup in which th captured plankton is collected. A device as described was used b aquanauts in the Helgoland and Tektite II programs.

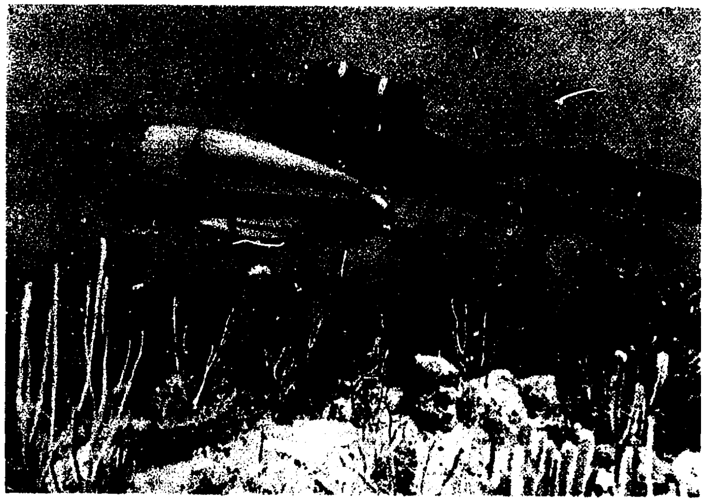
The Tektite II aquanauts collected plankton three times each day -- at 0900, 1300, and 2200 hours -- at five stations. An aquanaut would tow the net behind himself, holding it at a distance of about 15 cm from the seafloor. Towing duration and speed would be calculated to run 1 cubic meter of water through the net at each station. The samples, taken to the undersea habitat, were rinsed clean with water, fixed in a 4-percent Formalin solution, and then processed.

Three Hydrolab teams conducted in August and October 1972 and May 1973 repeating series of studies of the composition and distribution of zooplankton around the habitat site.

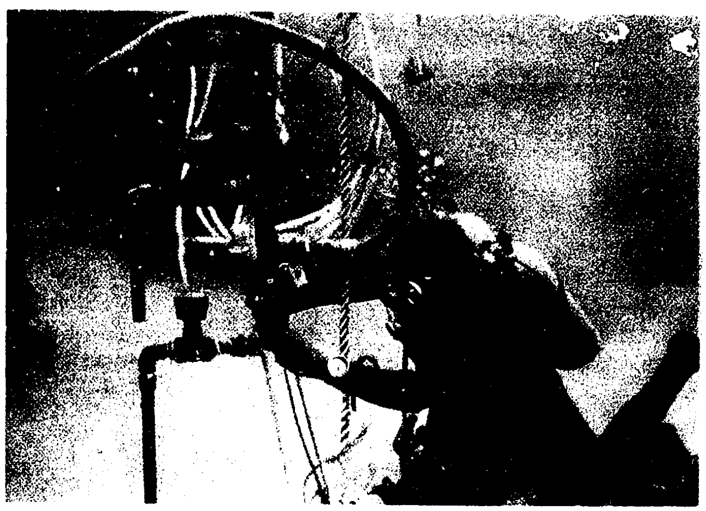
The aquanauts used in these experiments a towing vehicle made by Farallon with two plankton nets suspended from this vehicle. An aquanaut, steering the tow vehicle, would collect plankton on two preselected routes: to the south of the habitat, above sandy seabed (1 meter from the bottom), and to the north of the habitat, above the reefs (3 meters above). Route length was 100 meters. Plankton was collected twice each day -- at noon and midnight. Habitat aquanauts collected a total of 32 series of zooplankton samples.

At the same time as they were collecting zooplankton, aquanauts collected background hydrologic data -- they measured water salinity, recorded tide phases, and recorded water temperature in the two areas -- at depths of 9.4, 11.1, 13, and 15 meters on one plankton collection route and at depths of 11.3, 17.0, 22.9, 24.4, and 26 meters on the other route. The microstructure of the water mass temperature field was determined in the immediate area of the habitat. Current velocity and direction gauges were placed on both plankton collection routes. They were unable to measure content of dissolved oxygen in the water because of damage to equipment.

The most complex equipment for collecting plankton was employed by the Tektite I aquanauts. The purpose of the investigations was to study diurnal vertical migrations of zooplankton. At a distance of 10 meters from the habitat the aquanauts set up a PVC pipe perpendicular to the seafloor. Its upper end was secured to a float, and the lower end to a 1,150 kg anchor placed on the seafloor. Beginning at a depth of 3 meters and running to the seafloor, water intakes were placed in the pipe, shut by valves controlled hydraulically from the habitat. A 190 l/min water pump fabricated of plastic pumped water from the pipe through a hose into the habitat, where the water ran through a string of filters. Plankton settling on the filter screens would be processed -- counted and identified. Thus the aquanauts were able, without leaving the habitat, to obtain samples of plankton-containing water from various depths.



Hydrolab aquanauts collected plankton with the aid of two plankton nets secured to the hull of an underwater tow vehicle



System for remote collection of plankton samples at various depths, set up 10 meters from the Tektite habitat.

This setup kept experiencing problems, however, during the course of the experiment. At the very outset the pump was mistakenly started up "dry," that is, without water to lubricate the plastic friction parts. The pump broke down and was not replaced by a new one until the experiment was half through. On the 18th day of the habitat team's work tour, the current tore the pipe and water intakes off the anchor. The aquanauts found it, repaired and reinstalled it. The unit was fired up only 15 days before the experiment ended, thus operating only two weeks instead of the scheduled eight.

We should note one additional method of studying zooplankton -- the method employed by the Precontinent-2 aquanauts in 1963. The aquanauts, with the aid of a hand plankton net, collected samples of water with zooplankton into a matchbox-size transparent specimen holder. The specimen holder would be placed on the stage of a submarine microscope coupled with a motion picture camera. This setup makes it possible to record the appearance and behavior of the tiniest animal organisms in their natural environment.

Aquanauts have also employed the simplest method of studying plankton: through a habitat viewing port. Biologist Uhlig, a Helgoland habitat aquanaut, used this method to observe puzzling objects, large quantities of which were drifting with the current in the water mass. These objects were externally similar to either fine flexible threads 5-10 mm in length with a rounded bulge at one end, or rounded conglomerates 3-5 mm in diameter. Aquanauts were unable to collect these objects, however, for they were of such a fragile consistency that they would disintegrate immediately upon an attempt to place them in a specimen container.

Aquanauts have gathered plankton in all weather, day and night. At night they would sometimes attract plankton with a light source. The aquanauts working on the Tektite II program, for example, employed a 10,000 lumen lamp with a color temperature of 2000°K. The lamp was equipped with three removable filters: blue, yellow, and red. All three filters had a light transmission coefficient of 85. Two sets of lamps with a set of filters provided a capability to obtain 16 color combinations, including white. All 16 colors were tested in the course of 30 minutes. Zooplankton attracted by the light was collected with a plexiglass syringe and placed into two-liter containers.

The experiment indicated that zooplankton is most "attracted" by blue light, while red light seemed to frighten it off.

This observation was of great applied significance: by attracting plankton with light, one can also attract the fish which feed on it.

Microbiological investigations are fairly closely linked with observations to determine the composition and distribution of plankton in the sea.

A very interesting method of studying bacteria inhabiting the seafloor-adjacent water layer and the seafloor proper was employed by one of the "La Chalupa" habitat teams. Aquanauts determined the composition of the microfauna and microflora directly in the water, with the aid of an underwater microscope.

Microbiological investigations performed by the aquanauts of the Helgoland habitat, however, are more typical.

To collect water samples for bacteriological analysis, the aquanauts employed prior-evacuated glass containers with a water intake in the form of a small-diameter soldered tube. An aquanaut, taking a sample of water or "liquid seabed," places the tube into the layer of interest and knocks off the soldered portion with the end of his knife. Water enters the container due to the pressure differential between the evacuated container interior and the ambient pressure, filling it until the pressure of the air remaining in the container equalizes with the outside pressure.

Presterilized Petri dishes, delivered to the site in a polyethylene packet, were used to collect samples from the seabed surface. At the sample collection point the aquanaut would open the packet, turn the Petri dish over and push it into the seafloor to a depth of 1 cm, and then cut the column of soil which had entered the dish, without moving the dish, and cover it. The aquanaut would approach the sample collection point only against the current, in order not to disrupt the integrity of the sample.

Examination of the samples collected by the aquanauts showed that the composition and quantity of bacteria in the water are determined by the tidal activity phase and, in addition, by seafloor microtopography: quite different bacteria may be found even in small adjoining seafloor areas. As experience showed, the maximum density of bacteria is observed in a seafloor surface layer 2 mm thick.

A comparison of samples obtained by aquanauts with samples taken from the surface with a bottom sampler at the same place and at the same time indicated that they differ substantially from one another. In all cases without exception the samples taken by the aquanauts show a higher content of bacteria, sometimes double. It is interesting that such a discrepancy is also discovered with a comparison of data obtained by different methods on losses of organic matter during calcination and on the content of nitrogen and carbon in seabed sediments.

Apparently such a substantial difference in sample analysis results is due to the fact that the structure of the sample is disturbed during capture of the sample by a bottom sampler and, in addition, it is partially washed out with water during ascent to the surface.

One should also note that the results of analyses of the seabed-adjacent water sampled by aquanauts show greater stability than the results of analysis of samples taken from a ship. This is due to the fact that from the deck of a ship it is difficult to place a water sampler precisely into the target layer: the water sampler either actuates far from the seafloor or goes into the seabed, while aquanauts collect water samples easily and with a high degree of accuracy even at a distance of 1 cm from the seabed.

Applied hydrobiology. The problem of man-caused pollution of the sea was studied by undersea habitat teams in two areas. One of these areas was evaluation of the effect of purely mechanical water pollution accompanying harbor and shore reinforcement activities on the overall states of the marine animal and plant world. The second area is study of the physico-chemical effect of the products and waste from man's commercial activity, such as city sewage effluents, insecticides such as DDT, petroleum and its compounds, on marine life.

Both studies were chiefly of a methodological nature, but in many cases they produced valuable practical results.

Conducting marine pollution studies, in most cases aquanauts used primarily the same instruments and methods employed in working on problems of basic marine biology.

The method of investigating the metabolism of bottom-dwelling individuals and communities with the aid of respirometers proved to be highly suitable for studying a great many applied problems, including problems of environmental pollution.

The aquanauts of the FLARE program conducted studies for the purpose of determining the influence of man-caused factors on the "health" of a coral reef. They selected two sections of reefs at a depth of approximately 12 meters: one was in the natural state, while the other was in water with considerable turbidity caused by commercial activities in coastal areas.

First of all the aquanauts set up six respirometers on the unpolluted reef. Concomitantly they recorded a number of the area's hydrologic characteristics. The obtained data enabled them to calculate intensity of photosynthesis and respiration, which were adopted as background values.

As soon as the background was determined on the "clean" reef, the undersea laboratory and aquanauts shifted their operations 22 miles north, to the reefs off the famous sands of Miami beach. On one of these reefs they performed a series of observations analogous to those on the "clean" reef, but their result was quite different. The reef proved to be decolorized, partially dead, very poor in life -- there were practically no algae or young fish, and only an occasional adult fish was in evidence. On the whole the reef was similar to reefs in Micronesia which have been invaded by crown of thorns starfish. FLARE program biologists believe that the reason for such a contrast between two coral reefs located only about 20 miles from one another is the sharp, almost twofold difference in the quantity of light energy received by the "healthy" and "sick" reefs.

Turbid water, blanketing the sick reef like a cloud, hinders penetration of daylight from the sea surface. For this reason there are lacking on the sick reef, in contrast to the healthy reef, microscopic algae -- symbionts of the corals -- which play a very important role in the reef ecosystem: algae are nourished by the products of the vital activities of corals and in the process of photosynthesis release oxygen and dissolved nutrients, which are essential to the corals. Instruments recorded the absence of photosynthesis; consumption of nutrients by the corals exceeded their inflow, since the corals were deprived of symbionts.

Thus the biologists established that the primary cause of reef sickness is water turbidity caused, in the biologists' opinion, by operation of dredges in coastal waters, by harbor construction, and by the transport to sea of polluted water from ports.

Studying the influence of commercial and domestic pollution on the ocean, the Hydrolab aquanauts developed a method to determine the effect of petroleum and urban effluents on benthic biological communities.

The aquanauts prepared and applied to the surface of the seafloor several different mixtures of crude oil and reagents which "render" crude oil, in order to determine their effectiveness, physicochemical aging of the compound formed during the reaction, its solubility, vertical and horizontal mobility.

In a week's time the aquanauts were able to examine approximately 20 percent of the oil, applied at 30 different locations. They discovered neither any significant loss of oil precipitating reagent nor indications of aging of the resultant compound and determined that it migrates neither along the surface of a sandy seabed nor into it. It was also established that some species of marine animals react to the compound produced during settling out of the oil onto the bottom, but this compound does not exert significant toxic effect.

The next team manning the Hydrolab habitat investigated the effect of industrial and urban effluents on coral reef biological communities. The aquanauts determined that in the water layer adjacent to effluent-polluted areas of seabed the content of dissolved oxygen is two to three times that in bottom-adjacent waters over a clean seafloor. Vertical and horizontal migration of water masses with a reduced oxygen content exerts an adverse effect on the flora and fauna of this area.

One of the most important jobs to be accomplished today is to achieve more efficient and rational utilization of the sea's biological resources. The primitive technique of catching food in the waters of the seas and oceans -- blind harvesting without considering resource reproduction capabilities -- has revealed its reverse side: the sea's fisheries resources are steadily declining. This sad fact is universally known today. The only possibility of preserving the ocean as a food base for mankind is to transition to sedentary "mariculture," to the establishment of underwater farms and plantations and controlled undersea production operations.

It is evidently entirely possible (proven by experience in Japan) to rear marine animals on such farms until such time as they are able to live in the sea on their own, and when the young grow to a size of commercial significance, it is possible quickly and efficiently to catch fish and other commercial animals of the sea -- to "gather in the harvest," so to speak.

The work performed by a number of habitat teams was aimed at solving these problems, as an aggregate or separately.

It is a known fact that various shelters on the seafloor attract fish and bottom-dwelling animals. This is precisely the reason for the significant difference in the size of populations on rocky and sandy areas of the seabed. Rocks provide food and shelter, while sand does to a much lesser degree. Therefore one could assume that man-made structures on a sandy seafloor would attract a considerable number of living organisms; this would extend their range, leading to decreased density of "habitation," while this in turn would result in increased reproduction and ultimately a growth of population.

The first undersea habitat teams noted that their habitats were attracting inhabitants of the seafloor and the bottom-adjacent water layers. The aquanauts of the Sealab II habitat established during 45 days of working at a depth of 60 meters that the number of fish selecting as a permanent residence nooks and crannies on and about the habitat structure was 35 times the average number of fish on sandy seabed in that area. On a 500 square meter area around the habitat the number of sea bass increased from 400 on the fifth day of observation to 1,650 on the 43d day. The number of California perch increased during that same time from 500 to 2,800.

Aquanauts working out of the Chernomor habitat also noted on numerous occasions that fish and crabs were drawn to the habitat.

The Edalhab (FLARE program) habitat team studied the dynamics of colonization of an artificial reef.

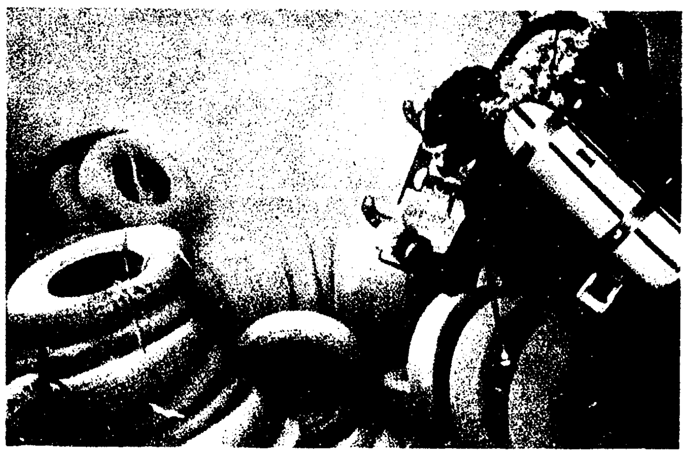
A "handmade" reef was constructed at a depth of 15 meters out of 500 old car and truck tires bound into bundles of from four to eight tires each. Concrete ballast was cast in one of the end tires, so that the entire bundle would stand vertically. The artificial reef occupied approximately 60 square meters of sandy seafloor. The aquanauts observed the artificial reef on two occasions -- one month and three months after it was built. The comparative results of these visits proved highly interesting.

Aquanauts spent four days on the reef during the first visit. During this time they saw only young fish ranging from 2.5 to 7.5 cm in length, which had found refuge in the tires and which were feeding on algae which had begun to grow over the "reef." There were no adult fish on the reef, and predator fish visited the site only by chance.

The picture had changed by the second visit. First of all, adult fish had appeared on the reef, up to 1 meter in length and weighing up to 16 kg. Secondly, the total number of fish species inhabiting the reef had increased from 20 to 30, and species of commercial significance had appeared. The reef's vegetation cover had also experienced considerable growth.

FLARE program biologists believe that in two or three years the man-made reef will be just as densely populated as a natural reef.

Of considerable practical significance was investigation of the reaction of fish to bottom traps, and consequently investigation of the effectiveness of bottom traps, conducted by the aquanauts of the Tektite program.

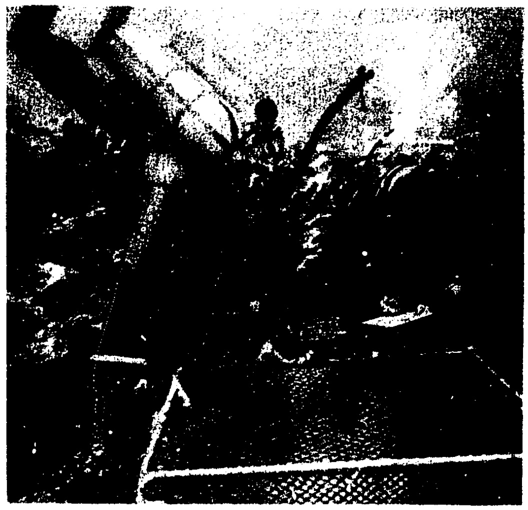


Aquanauts inspect an artificial reef formed of sunken automobile and truck tires

The aquanauts tested the trapping effectiveness of three bottom traps of the lobster pot type. One of them is extremely popular among Virgin Island fishermen. It comprises a net drawn onto a wooden frame measuring 0.5 x 0.9 x 2.7 m. The trap of the second type is in the form of a folding aluminum frame measuring 0.9 x 0.9 x 1.8 m, with a net stretched on it. The third type of trap is a molded latticed plastic cylinder 0.30 m in height and 0.83 m in diameter.

The aquanauts were seeking to determine the optimal trap location, best bait, and of course best type of trap.

The traps stood on the bottom approximately 230 hours on the average. A total of 130 fish were caught by the Virgin Islands type traps, while the experimental type traps caught 68 fish, but they were appreciably larger. The third-type trap, the only commercially-manufactured one, proved totally ineffective.



FLARE program aquanauts evaluate the effectiveness of an experimental-model lobster pot type trap

By altering trap location, the aquanauts ascertained that this is the most important factor determining its effectiveness. Moving a trap to the side (in some cases by only 1.5 m) increased a trap's daily catch from 5 to 25 fish. On the whole the aquanauts reached the conclusion that the optimal location for a trap is sandy bottom between two reefs.

It was unexpectedly learned that the type of bait does not influence a trap's effectiveness; in addition, traps containing no bait at all proved to be no less effective in catching fish. Studying the factors motivating fish to enter the traps, the aquanauts isolated the following stimuli: utilization of a trap as refuge upon entering "foreign territory"; random fish wanderings; curiosity; the herd instinct, when an entire school follows a single fish which has entered a trap; flight from a predator; attraction of a predator by a fish which has already entered a trap.

Upon entering a trap, fish would begin swimming in a circle, seeking a way out. Some species simply tore a hole in the net and departed, while others exited through the trap's entrance cone.

There was considerable variation in the time for the first fish to enter the trap, but the other fish followed the first in rapid order. After approximately 25 fish had entered the trap, "saturation" occurred. New fish ceased entering, although it was far from full. During daylight hours the traps were more effective than at night.

In 1971 studies of the effectiveness of bottom traps were continued by the Hydrolab habitat team. On the whole the results obtained by the Tektite aquanauts in the Virgin Islands were confirmed by observations in the Bahamas.

Finally, the Helgoland program aquanauts performed interesting experiments with raising young lobsters.

These experiments were begun by German biologists in 1969. These scientists were interested in two items: the innate ability of lobsters to gain their bearings under water, and possibilities of raising lobsters in man-made structures placed in the sea.

In a series of experiments pertaining to the first problem, aquanauts placed in a preselected area of seafloor two-year-old lobsters which had been raised in the laboratory and which had been placed in the sea for the first time in their lives. The seafloor experimental area was surrounded by a continuous ring of traps. No matter what direction in which a lobster moved, sooner or later it would enter one of the traps, and this made it possible to determine its direction of travel.

As it turned out, the overwhelming majority of these two-year-old lobsters, who were seeing the sea for the first time, wandered northwest, remaining in a sector between 30 and 60 degrees wide. The area in which Helgoland fishermen suspect the lobsters breed is located precisely in this direction, 20 km from the island of Helgoland.

In addition to an orientation ability, Helgoland program aquanauts studied the possibility of raising lobsters in the sea. For this purpose biologist Jatzke designed and tested under actual conditions an incubator for hatchlings and young lobsters and other marine animals. The incubator comprises a vertically-oriented cylinder 0.45 m in diameter and 0.5 m tall, made of plexiglass. The cylinder contains a system of inlet and outlet apertures and baffles positioned in such a manner that the current flowing past the incubator creates within the cylinder a circular water circulation movement. The natural flow of water through the interior of the cylinder delivers food to animals inside it.

Tests of the incubator demonstrated that its operating principle had promise, and at the present time a new model several meters in diameter and height is being readied for sea testing.

Experimental Geology

Geological research conducted by aquanauts can in general be grouped into several basic areas. First there is study of the processes of sedimentation and sediment transport. A second area is collection of samples and bottom coring for the purpose of studying the structure of deep seafloor strata. The third area is evaluation of the effect of living organisms inhabiting the surface and interior of the seafloor on the structure of sediments. Naturally all these investigations would be accompanied by preparation of a bathymetric map and geologic map of the seabed around the habitat site.

Evidently the processes of sedimentation and sediment transport were studied the most thoroughly by teams working on the "Chernomor" program.

The "Chernomor" aquanauts, working year after year, for a period of seven years, at depths of from 15 to 30 meters, stated and solved a great number of lithodynamic problems. They collected a wealth of material on dynamics of seabed topography and microtopography, accumulation and removal of clastic material, studied the mechanical composition of suspensions and mechanical differentiation of sediments in profile, and determined a diagram of velocities of bottom currents and intensity of movement of unconsolidated material along the seabed surface. Within the entire cycle of investigations running several years, the aquanauts performed several repeat cycles of measurements, which made it possible to construct a fairly accurate picture of summer-fall lithodynamic activity in the Blue Bay area -- a typical area in the northern part of the Black Sea coast of the Caucasus.

Observations of these processes were conducted in experimental areas set up by the aquanauts at depths of 10, 15, 20, 25 and 30 meters.

The typical "Chernomor" geological research area is set up as follows. In a selected area of seafloor aquanauts mark out a square 20 meters on the side and divide it into smaller five meter squares, thus obtaining a network of points. The position of each point is fixed in relation to a main reference point. The latter is in the form of a steel rod 1.75 m in length, driven 0.75 m into the seafloor. A movable cylindrical frame of thin wire is placed on the rod. The frame rests freely on the seafloor, and as the bottom washes out, it descends in conformity with the new position of the seafloor surface. A plate bearing a serial number is attached to each reference-mark rod.

Red-painted pebbles, sand coated with a light-yellow phosphor, and whole shells were placed in a monolayer in the center of each research area, in 1-meter squares. In addition, suspended matter collectors were mounted in the center of each area on supports, 20 cm and 3 m above the seafloor.

The geological research area at a depth of 30 meters was additionally equipped with a mast 6.5 meters in length. Suspended matter traps and self-contained current velocity and direction recorders were mounted on the mast at a distance of 0.5, 1, 2,3 and 4 meters above the seafloor.

Analysis of numerous measurements performed by "Chernomor" habitat teams in the research areas and of the samples collected by the aquanauts made it possible to draw a number of conclusions which are very important for geologists and geomorphologists.

It was discovered that alternating processes -- washing out of sediments following heavy gales and accumulation of material following light gales -- took place only in the research area at the 10-meter isobath. The seafloor zone with depths between 15 and 20 meters is a zone of stable accumulation of clastic material. The depth of maximum sediment accumulation, although it varies in relation to the force of gales, does not go beyond the indicated isobaths. Accumulation of material is considerably weaker at depths of 25 meters and more.

Results of investigation of processes of sedimentation based on measurement of fluctuations in seafloor profile in the research areas were also confirmed by the readings of the suspended matter traps mounted in the research areas. In a year's exposure, suspended matter traps at depths of 10 and 15 meters collected a layer of sand settling onto the seafloor up to 27 cm thick, while at a depth of 20 meters the suspended matter trap "caught" 13 cm of sand, and at a depth of 25 meters -- only 7.5 cm.

Examination of soil specimens taken at 5 meter intervals in the research areas indicated that the mechanical composition of the soil is highly variable. Even adjacent samples differed considerably from one another in distribution of sizes of particles forming the soil. The aquanauts also noted that at all depths large particles predominate on the seafloor surface following heavy gales, while medium-grain and fine-grain material predominates during mild weather or light swell. These observations are of great practical significance: the sharp fluctuations in structure of sediment surface layers discovered by the aquanauts place in doubt the reliability of existing methods of soil surveys from the ocean surface by collecting isolated samples, utilized for preparing a large-scale soil map for engineering-geological purposes.

The geological investigations performed by the "Chernomor" aquanauts were accompanied by a survey of the hydrodynamic background in seafloor-adjacent water layers with the aid of BPV current velocity gauges and velocity head sensors. The sensor readings, recorded in the habitat, indicate that water flow velocities in the bottom-adjacent 1-4 cm layer are very high -- up to several centimeters per second, while their magnitude and direction pulsate at frequencies close to those of the waves passing on the sea surface. There were noted several instances of high -- up to 0.7 m/s -- current velocity in bottom-adjacent water layers even in calm weather.

The effect on seabed sediments of bottom-adjacent currents and the "echoes" of waves passing on the sea surface is only one of the factors causing qualitative and quantitative changes in sedimentation processes and in the structure of seabed sediments. Also of substantial interest for geologists is biogenic influence on sediments, the influence of living organisms inhabiting bottom-adjacent water layers, the seafloor surface and within the seabed, on the structure of the seafloor.

Numerous examples of biogenic influence on the sediment surface and interior were also known previously. The parrot fish, for example, which feeds on corals, carries great distances a significance quantity of coral detritus, which they have first ground to the size of sand particles. Other fish and mollusks use fragments of corals and rock to build burrows and shelters, carrying them distances of up to 9-12 meters. Invertebrates and worms actively burrowing in the seafloor lead to disturbances of the seabed topography and structure. The quantitative aspect of biological processing of the seabed surface and interior was not clear, however, and therefore Tektite program aquanauts decided to study the degree of influence of reef fauna on the seabed structure.

The habitat team set up a research ground in the area of a coral reef it had selected as "subject." The research ground consisted of several areas of seabed surface artificially created by the aquanauts. Thus the Tektite habitat was positioned at the center of a complexly-organized geological research area with a number of artificial structures placed at typical points on nearby reefs. Regularly observing these artificial structures, the aquanauts were able to collect considerable quantitative material.

The aquanauts employed painted sand to study the biogenic transport of seafloor material. Several meters from the edge of the reef they poured a 500-gram cone of sand colored by red fluorescent paint. A medal peg marked the center of the cone. At another location a ridge of 1,000 grams of colored sand was placed crosswise to a channel with a gradient of 1:9 which cleaved the reef. The channel was then partially filled in with regular sand.

A year later aquanauts took samples from the experimental area they had set up. They determined that biogenic transport takes place differently on flat and sloped sections.

At horizontal locations the marked sand spread in all directions from the center of the pile. In the absence of currents, such distribution indicates that animals burrowing in and crawling on the seafloor displace material in a random fashion.

In sloping areas, such as in the reef channel, material displaces downslope. This is due to the fact that during processing of seafloor material by benthic animals, particles of material become suspended in the water and, subsequently settling onto the bottom by gravity, they displace downslope.

On loose soil samples are collected with a hand sample collector.

Samples taken by a sampler indicated that in a year's time the surface layer of sand in the channel had displaced a distance of approximately 50 cm, while during this time from 10 to 20 liters of sand had passed through just one surface layer 2 cm thick along a channel 2 meters wide. This volume of sand displaced by bottom-dwelling organisms is of course small, but a considerable quantity of material can move downchannel during a more extended period of time.

In those four seafloor areas most typical of the given reef, eight rows of sand ridges were poured, simulating the ripples which form on a sandy seafloor under the effect of waves and currents. The ridges were 5 cm in height, 100 cm in length, and spaced at 20 cm intervals. These artificial forms of microtopography were not subjected to the action of waves on the surface or bottom-adjacent currents. Nevertheless the ridges disappeared within 15 days at the mouth of the channel cleaving the reef, and within 24-35 days in the other areas. The investigators are inclined to ascribe the disappearance of ripple signs to the activity of burrowing organisms in the sandy seabed or animals crawling along the seafloor surface.

Thus the conclusion of the presence and force of bottom-adjacent currents solely according to the presence of a wave ripple on the seafloor may prove inaccurate.

One can judge the hydrodynamic activity of an area to some extent by the location of empty shell halves on the seafloor. In those places where wave action penetrates to the seabed or there are currents, shells assume the most stable position on the seafloor -- concave side down. In calm water shells are positioned at random, without a predominant orientation of the concave side. Usually one judges the relative "activity" of the sea in the past from the position of shell halves in ancient sediments.

The aquanauts placed 120 empty shell halves in four seafloor areas -- two areas 2 meters from the reef, and two areas 6 meters from it. In two areas -- one of each pair -- the shells were placed concave side upward, and in the two other areas -- concave side downward. Forty days later the aquanauts recorded the position of the shells. A count of the experiment results indicated that the majority of the shells -- more than 70 percent -- lay concave side downward, and most of these were large shells, rounder and more concave. Approximately one half of the shells ended up under the surface of the seafloor. We should note that during the entire time of the experiment there were practically no currents or waves in the experiment area, and consequently all changes in position of the shells could be due only to the activities of living organisms dwelling on the seafloor.

The experiment showed that the degree of biogenic influence on the position of shells is very high, and this factor must be taken into account in determining the hydrodynamic activity of an area on the basis of the position of shells.

Another important indicator frequently utilized by geologists in studying processes on the seabed, for calculating rates of sedimentation in the given area, for example, is depth of burial in the sandy seafloor of solid fragments of rocks, corals, etc.

In each of the experimental sections aquanauts placed on the seafloor 22 fragments of various shapes and sizes: from spheres approximately 4 cm in diameter to flat rounded pebbles measuring approximately 5 x 10 cm. The position of each pebble was recorded 32 days later. An analysis of the position of the fragments indicated that the rate of burial in the sandy seafloor was quite substantial. On the average each stone was imbedded 2 cm into the seafloor, and some fragments as much as 8 cm. Aquanauts noted that the depth of burial is not related to the size and density of the fragments but depends solely on their shape and the structure of the seafloor. Flat fragments become imbedded more rapidly; the smaller the particles of the substratum forming the seafloor, the more rapidly burial occurs.

On the whole this experiment, just as the experiment with wave ripple and shell orientation on the seafloor, indicated that when dating strata, calculating sedimentation rates, etc on the basis of analysis of the position of fragments in a sandy seabed, it is necessary to consider biogenic effect on the depth of occurrence of a fragment within the seabed. As we know, the very fact of the presence or absence of clearly-marked layers within a sequence of seabed sediments can tell a great deal to the geologist, and in particular can indicate to him, for example, the force and distribution of gales in the zone being studied, the force of currents, etc.

An artificial stratified structure was given to the seafloor in those same four areas. To achieve this, aquanauts dug a hole 100 cm in length, and 25 cm in width and filled it with four alternating layers of colored sand 2 mm in thickness and local, uncolored sand, 3-5 mm thick.

Every four days the aquanauts removed from the seafloor locations with the artificial stratified structure whole sand sections measuring 5 x 15 x 15 cm. Observations indicated that the top 5 mm of sediments are completely processed by seafloor-dwelling organisms in only four days. The rate of mixing of layers decreases with depth, but it still remains fairly rapid. Consequently one should be extremely cautious about drawing any conclusions in areas of high biological activity on the basis solely of absence of stratification of the upper part of the seafloor sequence.

On the whole the Tektite program geologists firmly established that reef-dwelling organisms play a very important if not the most important role in transport, distribution and processing of sediments on the seafloor adjacent to a coral reef.

One of the classic tasks of marine geology is study of the deep structure of the ocean floor, with collection of specimens for subsequent analysis in the laboratory. It would seem that there is nothing particularly complicated about obtaining a specimen of rock from the ocean floor -- a drill ship or drilling platform goes out to the area of interest to geologists and drills into the ocean floor, bringing up to the surface core samples of the rock underlying the seabed. This operation has been performed on numerous occasions in exploring for and producing oil in offshore oilfields, and the process proper of drilling at continental-shelf depths no longer presents a problem.

The operating cost of drill ships and drilling platforms, however, is quite high, and every hole drilled into the seabed involves enormous outlays. The cost is justified when producing oil -- the oil will repay all costs. Such drilling is an excessive luxury, however, at the present for scientific research. There exists only one drill ship whose operations are of a specifically research nature -- the "Glomar Challenger," but it costs so much to operate that operations are financed by the combined resources of several countries.

There is a method which enables one to solve the problem of ocean floor drilling comparatively easily and efficiently -- it is employment of drilling rigs set up on the seafloor and operated by aquanauts.

The first attempts at drilling directly on the seafloor were undertaken in 1967 by "Ikhtiandr" program aquanauts (USSR). Later, in 1969, activities with the "Ikhtiandr" drilling rig, built at Donetsk State University, were included in the "Chernomor" program of the USSR Academy of Sciences Institute of Oceanography. With this drilling rig aquanauts drilled a hole 11.2 meters deep and took samples of the rocks through which the hole was drilled.

The drilling rig was based on the GP-1 land drilling rig. A PShR-12 compressed-air motor was employed to drive the drill rod. All equipment was mounted on a three-support frame placed on the seabed. The underwater drilling rig weighed 650 kg assembled; maximum working depth -- 30 m; drilling depth -- 20 m; hole diameter -- 76 mm. In testing the underwater drilling rig, "Chernomor" aquanauts sank a hole 11.2 meters deep in short order. In the course of drilling they obtained core samples from depths of 5-6, 8-10.5, 10.5-10.9, and 10.9-11.2 meters.

Working on the "Shelf-Chernomor" program in 1974, aquanauts drilled several boreholes in the vicinity of the undersea habitat at seafloor depths in excess of 20 meters. In this experiment they employed a drilling rig operating on the principle of vibration drilling; it was designed and built at the underwater research laboratory of the Varna Institute of Fisheries and Oceanography.

The rig consists of a frame 3 meters in height, with four supports, on which it is mounted on the seafloor. A vibrator block, the upper end of which is connected to the drill string, travels on guides along the frame. The drill string penetrates the ground under the effects of these oscillations and its own weight. The diameter of the drill string is 65 mm, and joint length is 2 meters. Adding joints manually as the hole advances, one can drill as deep as 25 meters in sandy seabed.

The rig requires 3 kilowatts of power and is operated by a single person. One person can also move the rig from site to site. During the "Shelf-Chernomor" program aquanauts drilled boreholes at three different seabed sites near the habitat and collected a total of 18 meters of core samples.

In 1972 FLARE program aquanauts drilled into the body of a coral reef. Using the Edelhab habitat as a work base, aquanauts inspected the coral reef and selected a site of interest. It was a natural channel cutting across the coral reef. With the aid of a pneumatic-hydraulic dredging device, the aquanauts removed a thick layer of sand lying on the bottom of the channel and exposed the body of the reef. Aquanauts then placed a hydraulic drilling rig with a diamond bit on the channel bottom and proceeded to drill into the reef. After several days of drilling they had sunk a borehole 1.8 meters deep; the drilling rate averaged 2.5 cm/h.

Studying the removed core samples, geologists concluded that several thousand years ago the reef was at a depth of 1.5-3 meters from the water surface; today it is at a depth of 15 meters.

The Seabed -- A Laboratory for Physicists

Geophysical investigations performed by aquanauts have, with few exceptions, dealt with two aspects of hydrophysics: hydrodynamics and hydrooptics.

We should note that aquanauts also took background data essential for completeness of observations in other scientific disciplines, biology or hydrochemistry, for example, measuring a number of seawater parameters according to programs close to those of standard hydrological stations.

In the Sealab II experiments, for example, aquanauts installed under water a group of measuring instruments with the aid of which they obtained continuous series of data on velocity and direction of currents and water temperature on a time axis, at two levels. Hydrolab aquanauts determined current velocity and direction, water temperature and salinity. These and other such measurements, however, were of a subordinate character; standard equipment was employed, and they could not be called an experiment in the full meaning of the term.

A principal aspect of hydrodynamic research conducted by undersea habitat teams was study of the microstructure of seafloor-adjacent currents.

This work was initiated by the Precontinent-3 habitat team. The undersea habitat aquanauts, at the request of France's Atomic Energy Center, were to attempt to determine the velocity and direction of bottom currents. It was assumed that although such currents exist, they are so weak that conventional current velocity gauges do not "sense" them.

Aquanauts placed a lightweight truss structure on the seafloor, in the upper part of which was placed a hopper filled with balls of very small, close to zero, negative buoyancy. A special mechanism periodically released a ball from the hopper. The balls would slowly descend to the seafloor, and during descent the bottom current would drift them from the vertical. A screen was placed on the seafloor directly under the truss structure; the balls would fall onto the screen. The stronger the current, the further from the center the balls would land. By counting the number of balls in the various screen squares, one could determine the prevailing current velocities and directions.

Processing of the experiment results indicated that bottom currents do exist in that part of the Mediterranean studied by the aquanauts and that their velocity is sometimes considerable. The data obtained by the aquanauts were utilized in selecting a site for burying in the sea radioactive waste from France's nuclear industry.

Hydrophysical investigations conducted by the "Chernomor" team also had as one objective study of the microstructure of bottom currents. Aquanauts placed a mast on the seafloor 50 meters from the habitat; on this mast they placed 14 wire strain gauges to measure the water velocity head, positioned from 2 cm to 6 meters from the seafloor. Signals from the strain gauges were transmitted by cable to the habitat, where they were amplified and recorded.

To measure current velocities below the sensitivity threshold of the strain gauges, the aquanauts took motion-picture photographs of the movements of dye-stained water on the background of a scale grid.

A light frame measuring 1.5 x 1.5 m with scale threads forming a grid with grid squares measuring 10 cm was placed on the seafloor and perpendicular to it. The frame's swivel suspension allowed it to orient itself to the current. Uniformly-distributed rubber containers of fluorescein dye were hung along the frame edge washed by the advancing flow of water. A special device released dye from all containers simultaneously. The aquanauts recorded on film propagation of the dye streams in the water against the grid background. Interpretation of the photographic record made it possible to determine absolute current velocities, distribution of currents in the bottom-adjacent 1.5-meter water layer, and turbulence within that layer. These data proved very important for geologists studying processes of sedimentation and sediment transport.

The largest volume of hydrophysical investigations performed by aquanauts is in the area of hydrooptics. Tektite, Hydrolab and "Chernomor" teams studied characteristics of the natural undersea light field, but the aquanauts of each of these programs pursued their own quite specific objective. U.S. aquanauts recorded undersea illumination as a background quantity needed by biologists. The hydrooptical investigations performed by the "Chernomor" aquanauts were of a more basic, academic character. The continuing program of hydrooptical research of the USSR Academy of Sciences Institute of Oceanography imeni P. P. Shirshov is unique in its way and merits particular attention.

Investigations of the natural light field under water have been conducted by the institute for many years now. Usually surface vessels are employed for these studies. However, the rolling and pitching of the vessels from which the instruments are lowered, their drifting, as well as the random and uncontrolled oscillations of the instruments themselves, suspended on a long cable below the ship, introduce such significant interference into the measurement results that it is very difficult to interpret them.

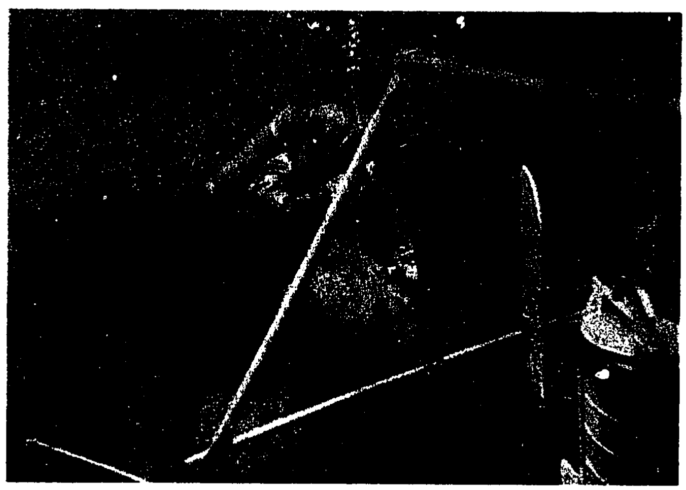
Only after it became possible to mount instruments on a rigid foundation on the seafloor were scientists able to obtain readings free of induced interference. However, operating and servicing of optical measuring equipment mounted on the seafloor requires a considerable volume of diver labor. It is therefore not surprising that precisely hydrooptics was one of the first scientific disciplines included in the "Chernomor" program.

During the first year of operation, the "Chernomor" habitat carried instruments to measure underwater illumination and luminance, degree and plane of polarization of the natural light field under water, and range of horizontal visibility. The habitat teams also recorded fluctuation in the natural light field under water under various conditions -- with differing sun elevation, changes in orientation of photometers relative to the sun, and intensity of surface wave action.

Estimating the results of measurements, hydrooptics scientists concluded that study of fluctuation in the natural light field under water can become the most interesting and promising area of hydrooptical investigations from an undersea habitat. From 1969 through 1974 hydrooptical studies in the "Chernomor" program pursued precisely this aim.

We should mention that this problem is interesting not only from an academic standpoint. Fluctuations in the natural light field caused by surface swell and shading of light detectors by clouds can produce interference for the most diversified underwater systems, such as undersea light communications and light detection and ranging systems.

Typical of hydrooptical investigations in the "Chernomor" program was placement of instruments on a firm foundation in the water mass -- a mast mounted vertically on the seafloor at a depth of 20-30 meters, with the mast top extending several meters above the water surface. A float and guy wires ensure a stable vertical position for the mast, fabricated of thin-wall stainless-steel pipe.



A "Chernomor" habitat aquanaut sets up a seafloor hydrological research area (photograph by V. Antipov).

The base of the mast is secured to the shaft of a turning device mounted on the seafloor. By turning a handle the aquanaut can orient the mast -- and the instruments mounted on it -- in an azimuthal direction.

A swivel bar attachment assembly is mounted at approximately the center of the mast. An aquanaut can rotate the bar in the vertical plane, changing its position from vertical, along the mast, to horizontal, across it.

Sensing devices are attached to the bar as specified by the research program. A transmissivity gauge and underwater illumination and luminance sensors have been placed on the swivel bar for research programs of recent years. Above-water luminance and illumination sensors, a wave recorder and anemometer were placed on that part of the mast which extended out of the water. A self-contained current velocity and direction gauge was placed on the seafloor close to the mast.

The laboratory team would mount the instruments on the underwater portion of the mast, lay cable to the habitat, monitor the instruments and spatially orient them in performing measurements. The habitat team also had to clean the light detector illuminators on a regular basis, as they would be fouled by marine algae within a few days after immersion.

All instrument readings were registered by automatic recorders on board the habitat. The aquanaut monitoring the recording and the team member servicing the mast and instruments on it maintained continuous two-way telephone communication.

During the entire period of operation of the "Chernomor" habitat hydrooptics scientists obtained approximately 300 series of records of fluctuations in the underwater light field, taken synchronously with recording of the state of the sea surface. These series of recordings were processed on a Minsk-22 computer and analyzed.

The obtained energy spectra of fluctuations in underwater illumination proved to be close to the energy spectra of the surface swell, and this similarity increased with an increase in depth of instrument placement.

Analysis indicated that high-frequency oscillations the amplitude of which is several tens of times less than the amplitude of the low-frequency component are superimposed on the low-frequency fluctuations in underwater illumination. It was also determined that the high-frequency portion of the fluctuation spectrum "smooths out" and disappears with increasing depth.

Hydroopticists are currently preparing an atlas of energy spectra of light field fluctuations under water. Scientists believe that they will also be able to solve the inverse problem -- to determine the state of the sea on the surface on the basis of a statistical description of the light field under water. The fact is that increase in surface wind velocity is clearly traced on the basis of changes in the spectra of fluctuations in illumination under water. Fluctuations in underwater luminance caused by an increase in wind velocity are as a rule even more clearly marked.

Experiments in recording high-energy cosmic particles, conducted by Hydrolab and PRINUL program teams, can serve as an example of a "non-standard" approach to utilization of the capabilities of undersea habitats.

Usually in studying such particles the Earth would be used as a filter which traps low-energy particles. Film cassettes would be exposed deep inside mines to record the tracks of collision of high-energy cosmic particles with atoms in the emulsion layer on photographic film, but different rock sequences possess different filtering characteristics, and this affected experiment results.

Physicists studying cosmic radiation drew attention to the fact that water by its nature constitutes a highly-effective, homogeneous filter. Low-energy radiation which pierces the Earth's atmosphere does not penetrate deep into water and, consequently, only high-energy particles are present in water beginning at a certain depth.

It was necessary to surmount one difficulty, however, before proceeding with experiments to record these particles under water. Cosmic radiation is omnipresent in the atmosphere. Therefore as soon as photographic emulsion is applied to film, background radiation begins acting on it. For this reason emulsion should not be applied to film on the surface and then sent to the bottom with divers -- the background radiation will affect the experiment results.

In 1972 physicists turned to oceanographers with the request that they be given the opportunity to perform a series of experiments at recording the tracks of high-energy cosmic particles, utilizing an undersea habitat as a base for making the recording film.

The Hydrolab habitat was chosen for this experiment, which was primarily of a methodological nature. Calculations indicated that a 15-meter water layer above the habitat was a sufficiently reliable filter.

In February 1973, switching off all lights in the habitat work compartment except for a red bulb, aquanauts prepared 40 cm^3 of highly-sensitive emulsion for exposure. The prepared emulsion was applied to photographic film in a layer 400 microns thick, on an area of 52 cm^2. The film plates were divided into two units, 20 plates each, and placed into watertight film holders. Then the aquanauts carried the film holders out into the water and placed one holder on the habitat's top deck, at a depth of 11 meters, and the other on the seafloor, at a distance from the habitat, at a depth of 30 meters.

In April aquanauts received the first film holder and processed the plates; the second holder was processed in May. The developed plates were sent for interpretation to the University of Washington. In May aquanauts also prepared and placed under water an additional pack of film plates, but this time at a depth of 45 meters. In August, after a four-month exposure, these plates were also developed and sent for interpretation.

Scientists at the University of Washington, studying the photographic plates under a microscope, discovered several tracks indicating passage and collisions of muons.

The success of this experiment prompted another series of experiments, this time at the PRINUL program "La Chalupa" habitat, which was sited at a greater depth -- 29 meters. However, due to humidity and the high temperature of the breathing mixture in the habitat compartment, the photoemulsion did not properly adhere to the film. The experiment was unsuccessful.

Nevertheless, this partial failure has not made the new method of recording high-energy particles any less attractive to physicists. Experts hope that in time it will be possible to place at a depth of 300-600 meters instruments which will be able to detect not only muons but also the elusive neutrinos and even problematical gravity waves.

They believe that such an experiment can be set up as follows. Aquanauts, in an undersea habitat at a depth of 30-60 meters, would prepare holders with packs of photographic plates, and then the plates would be delivered, say to a depth of 250 meters, by research submarine. Following exposure of the plates at this depth for a period of several months, a submarine vehicle would retrieve the film holders and return them to the habitat. Aquanauts would develop the film plates and ready them for interpretation.

Neutrino track detectors and Weber detectors for detecting gravity waves can be transported to the seabed directly from the surface -- they are incensitive to background radiation.

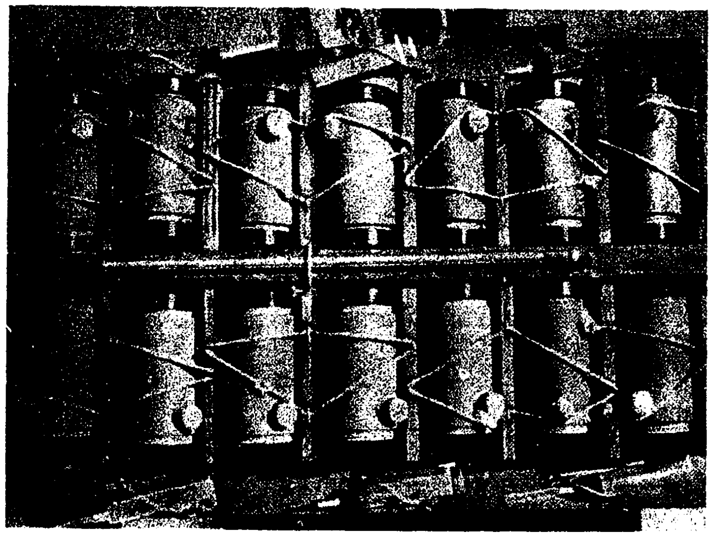
In Situ Hydrochemistry

For many years now oceanographers have been discussing the problem of preserving the integrity of a seawater sample taken at a given depth and brought to the surface. It has been conjectured time and again that a change in the content of the gases dissolved in seawater takes place in the process of bringing a sample up to the surface. This hypothesis also applies to the content of dissolved oxygen, and two explanations were advanced for causes of change: first of all, possible degassing of the sample, occurring due to a drop in ambient pressure and change in water temperature in the process of bringing up the sample; secondly, continuing biological activity of organisms trapped in the sample, leading to oxygen consumption.

Tektite II and Hydrolab aquanauts performed a series of experiments to test these hypotheses.

The aquanauts set two tasks for themselves: first, to evaluate the advantages of immediate fixing of the sample at the collection site and sample processing at the same pressure under conditions of a habitat standing on the seafloor, prior to sample fixing on the surface and, second, to obtain data needed by biologists and geologists on the pH of seawater, alkalinity, salinity, and content of oxygen, phosphates, calcium, and magnesium.

Two sites were selected for collecting samples: at the middle of a reef, on sandy seafloor surrounding a reef, and at the reef-sand interface. Over a period of 24 hours four samples were collected, three of which -- at 0600, 1200, and 1800 hours -- were collected by aquanauts, while the 2400 probes were collected by a diver from the surface. A total of approximately 800 samples were collected, 400 of which were processed by the habitat team, while the remainder were processed at the base camp on shore.



Water sampler holder, for taking water samples and fixing them in situ -- worn above diving gear.

The Tektite aquanauts utilized a set of hand-operated water samplers to collect water samples. This set consisted of a frame secured to the aquanaut's back above the breathing tanks; the frame contained 14 PVC water samplers of 225 ml capacity each. Each sampler was in the shape of a cylinder with screw-on lids providing a watertight seal. Mounted in the water sampler rim was a short tube with the tube opening covered by a rubber diaphragm. If it is necessary to add to a water sample a given reagent immediately after collecting the sample, such as for fixing it in situ, this is done with the aid of a syringe: the syringe needle pierces the diaphragm, and after the reagent has been introduced, the needle is withdrawn from the diaphragm.

Syringes with reagents and spare needles were secured to each holder frame.

Aquanauts, working in pairs, could take samples at 27 points, recording water temperature at the sample collection point. Subsequently samples would be processed in the habitat.

Aquanaut uses a syringe to pass a water sample through a container with a dissolved oxygen content sensing device. The instrument proper is located in the habitat.

Water salinity was determined with a HiTech bridge-salinometer; calcium and magnesium content were determined by titrating the sample; water pH was measured both in the habitat and on the surface, at the base camp, with a Beckmann instrument. Oxygen content was determined by titration employing the Winkler method. No phosphate content data was obtained, since the reagents proved to be damp.

The method of determining oxygen content in water was as follows. Aquanauts collected four samples simultaneously at each point. The first sample was fixed directly in the water and processed in the habitat. The second sample was also fixed and processed in the habitat. The third sample was fixed in the habitat and processed at the base camp on shore. And finally, the fourth sample was both fixed and processed on shore.

The results of averaging 24 series of processed samples, contained in Table 2, enable one to reach an unambiguous conclusion -- pressure change in the process of bringing a sample to the surface leads to degassing of the sample, with the oxygen content in the sample approaching its saturation limit for sea surface conditions -- 4.3 ml/1.

Table 2. Change in Content of Oxygen Dissolved in Water (ml O_2/H_2O) in Relation to Place Where Sample is Fixed and Processed

Place Sample Fixed	Place Sample Processed	Oxygen Content
In situ	Undersea habitat	5.26
Undersea habitat	Undersea habitat	5.26
Undersea habitat	Shore	4.32
Shore	Shore	4.22

In addition to clearly-marked degassing of the collected sample when fixed and processed on shore, the aquanauts also discovered two additional interesting phenomena.

It seems that oxygen content in water varies within a considerable range in the course of 24 hours (Table 3), and as a rule this change takes place fairly evenly. Sometimes, however, oxygen content in the water at a given point changes severalfold literally in a single bound. At first aquanauts discovered such a sudden change in oxygen content quite by chance, during night sample collection rounds. When the water sampler was already open, the light warm current suddenly and abruptly changed to cold water. The water sampler was immediately shut and the cold water sample fixed. Analysis of this night sample back in the habitat showed an oxygen concentration which was more than three times the concentration in a daytime sample.

Table 3. Change in Content of Oxygen Dissolved in Water (ml $Na_2S_2O_3$ solution) in Relation to Time of Day

Time of Day	Oxygen Content		
	Reef	Sand	Reef-Sand Interface
0600	2.93	2.98	2.94
1200	3.35	3.25	3.17
1800	3.25	3.27	3.25
2400	2.99	3.01	3.05

In addition, aquanauts established that oxygen content does not change over a period of three hours in a sample taken in an opaque water sampler and thus isolated from light: if it does not increase this indicates that photosynthesis processes have halted, and if it does not decrease this means that respiration of organisms in the sample has also stopped. After 3 hours have passed, oxygen content in the sample begins decreasing sharply.

Following publication of data obtained in Tektite II experiments, oceanographers expressed the supposition that the discrepancy in the data recorded by aquanauts on oxygen content in water with the quantities obtained by traditional methods could be due to two factors. First of all, they stated, modern technical means of taking samples make it possible to bring a sample to the surface so quickly that degassing of the sample does not have time to take place. Secondly, it is possible that the sample is affected by air expired by the diver collecting the sample, air which dissolves in the water in the process of expiration.

In order to verify these assumptions, Hydrolab aquanauts performed a series of control experiments. The experiment employed a transparent water sampler and a dissolved oxygen concentration measuring device.

Aquanauts placed the measuring device electrodes in the water sampler with a water sample located 7.5 meters from the habitat, while the measuring instrument proper was inside the habitat. At a water temperature of 27°C, oxygen content in the sample was 14 ml/l, which is close to saturation. On a signal given from inside the habitat, an aquanaut proceeded to surface together with the water sampler, stopping every 3 meters.

A drop in dissolved oxygen content in the sample was already evident at a depth of 9 meters (Table 4), a drop recorded not only by the instrument but also by the aquanaut: seeing gas bubbles forming in the sample, he photographed them. The dissolved oxygen content in the sample had dropped by 20 percent as a depth of 3 meters was being approached.

Table 4. Change in Content of Dissolved Oxygen in Water (ml/l) as Sample Is Brought to the Surface

Depth, m	Oxygen Content in Sample	Exposure, min
15	14.0	0
12	14.0	3
9	13.5	4
6	11.9	1
3	11.1	8

In the next experiment an aquanaut carrying a sample with an oxygen content of 13.2 ml/l ascended from a depth of 14 meters to a depth of 3.3 meters and remained there 3 minutes. After this time had lapsed, he released the gas which had been liberated from the sample and immediately fixed the sample. Processing of the sample in the undersea habitat by titration according to the Winkler method indicated that oxygen content in the sample had decreased by 12 percent.

Thus one can apparently consider to be sufficiently substantiated the assumption that degassing of a sample takes place as pressure is reduced in the process of bringing an unfixed sample to the surface.

Aquanauts from the "Sprut" habitat and scientists from the All-Union Scientific-Research Institute of Marine Fisheries and Oceanography conducted a similar series of measurements of the chemical parameters of seawater, supplementing it with measurements of rate of diffusion of oxygen in water.

They placed on the seafloor not far from the habitat, at a depth of 11 meters, two 80 cm tall 40-liter capacity containers. The area of the open mouth of the containers was 314 cm^2. In one container the dissolved oxygen content was artificially elevated 13 ml/l, and lowered in the other to 4 ml/l. In the first container oxygen content equalized with the level of its content in the ambient water in six hours, and in the second container -- in four hours.

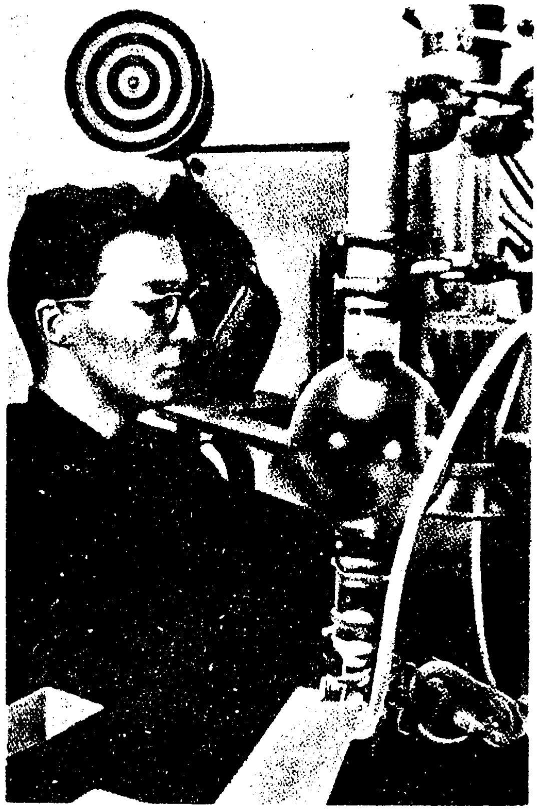
A total of five series of these experiments were performed. Change in oxygen content in containers at different levels was determined by means of analysis in the habitat of samples taken with the aid of capillary tubes.

Both the Tektite and "Sprut" aquanauts established that a decrease in oxygen content in water leads to a lower pH in the water and an increase of alkalinity and phosphate content.

The first hydrochemical studies in an undersea habitat were conducted during two weeks of the summer season, which could provide with adequate reliability only diurnal changes in the target characteristics for the summer. Data on seasonal change in target water characteristics at a given point in the sea could be of much greater interest, however. An undersea habitat located at one site and operating year-round would be a very convenient place to study seasonal changes in the parameters of seawater.

Proceeding from these considerations, a regularly-repeating series of hydrochemical observations was included in the 1972-1973 seasons in the work program of the Hydrolab stationary, continuously-operating undersea habitat. The purpose of this series of observations was to determine seasonal variations and relationships between dissolved oxygen content in water, water pH and content of carbonate system components. Concomitantly with these measurements, aquanauts were recording background data -- water temperature and salinity, as well as accumulation of the isotope carbon 14.

The series of measurements were repeated five times in the course of a year: from 1 through 7 August 1972, 1-7 October 1972, 1-7 December 1972, 1-7 March 1973, and 1-7 May 1973.



Chemical-analytical equipment was extensively utilized by habitat teams in conducting research.

Areas of reef 100 meters from the habitat were selected as sample base collection points. Nine sample collection points were positioned in three tiers; the lower tier was at a depth of 19 meters, and the upper tier at 13.2 m. At each of the nine points three samples would be collected simultaneously every four hours in the course of 5-6 days.

Taking into account the experience of the Tektite II aquanauts, Hydrolab habitat aquanauts fixed samples for dissolved oxygen in situ and processed them in the habitat. Water samples for salinity were transferred into transport containers and sent for analysis to the surface. Water samples taken at the same time for calculating primary productivity were fixed with Formalin and also sent to the surface for processing.

Research has shown that with weak and moderate surface swell the water column can be divided, by chemism, into two parts -- above and below 15 meters. The lower section extends from a depth of 15 meters to the actual seafloor, which in this instance lay in a depth of 21 meters, and the upper part runs from a depth of 15 meters to the surface. One should bear in mind that reef tops in the research area were below the 15 meter depth.

Evidently the difference in chemism between the upper and lower layers is caused by the fact that in the upper layer processes are determined by processes taking place at the "water-air" interface, while in the lower layer the influencing factor is the "water-seafloor" interface, as well as the vital activities of reef flora and fauna. With surface swell 1.5-1.8 m, the boundary between these layers begins to blur, and with swell greater than 2.4 m it disappears entirely, although elevated values of chemical characteristics are retained in the seafloor-adjacent zone, and reduced values in the surface layers. No influence of tides on these values has been discovered.

As long as the sea was calm, there was observed a good agreement between dissolved oxygen content in the water, the water's pH and general alkalinity. At high oxygen concentrations, water pH and general alkalinity dropped off sharply.

The fact that there are two clearly-marked maxima in the daily variation in concentration of dissolved oxygen in seawater was highly interesting and unanticipated: one -- the day maximum, occurs at 1400-1500 hours, while the other occurs at night. The night peak is possibly due to the fact that at night along-shore currents bring water with elevated oxygen content from the neighboring reef, located 4-5 miles away.

Chapter 3. AQUANAUTS AND SCIENTIFIC ORGANIZATION OF LABOR

Planning Experiments

Experiments conducted at sea and based on utilization of such a complex and expensive piece of hardware as a manned undersea laboratory require comprehensive, thorough preparation and detailed planning of all aspects of the forthcoming research. Experiment planning determines in large measure the useful outcome of the project and the volume of scientific information received by the habitat team.

One of the principal items is drawing up a program of scientific investigation. An undersea habitat, just as any other equipment-carrying hardware, has its advantages and drawbacks. In drawing up a work program it is essential to choose scientific problems and formulate the task for the habitat work team so that the advantages inherent in this type of equipment are displayed to a maximum degree, while the drawbacks and limitations do not affect the scientific data obtained. In other words it is necessary that the subject of investigation be in conformity with the methods capabilities of the undersea habitat.

The second task which must be accomplished in preparing for a research program is assembling a work team and organizing its activities. Selection of a work team is a complex task, and psychological compatibility among team members is not the most difficult problem, although the necessity of joint work activities by a group of individuals of very differing interests, who as a rule possess a highly developed intellect and, as a consequence, a developed sense of ego, enclosed in an undersea habitat, isolated from the outside world, brings up a great many questions which must be considered in preparing for research activities.

And finally, preparation of equipment: the habitat, support systems and auxiliary equipment, equipping the habitat with scientific apparatus, and furnishing the aquanauts with simple and reliable individual research equipment.

Choosing an Objective

Evaluating the experience of operation of undersea habitats and the nature of tasks performed with their assistance, we can isolate two basic elements which determine the specific features of the undersea habitat as a research means.

First of all an undersea habitat serves as a base enabling a diver to work in the water for several hours a day at depths of 100 meters and more. This is important, since the diver himself can be viewed as a highly-efficient means of investigation. Working in the water mass or by the seabed, the diver is able to coordinate his actions in space with a precision to 1 millimeter and in time with an accuracy of seconds, utilizing as a counting point any object suspended in the water mass or placed on the seafloor. Measurements performed by the diver are practically free of the errors which are inherent in measurements performed from a surface vessel (subjected to rolling and pitching, drift, vibration); in addition, the disturbing effect of the diver himself is reduced to a minimum, since he can move freely about over a substantial area.

Second, the undersea habitat -- its spaces, power supply, and microclimate parameters in the compartments -- make it possible to employ modern electronic, optical, and chemical analysis equipment. And this makes it possible to organize on the spot, under water, quantitative or qualitative study in situ of objects the structure and parameters of which are inevitably disturbed when specimens are collected from the surface and during subsequent processing on board surface vessels.

Naturally these considerations, which are general in nature, are patently insufficient to understand the place occupied by the undersea habitat in the overall arsenal of technical means at the disposal of oceanography.

Two methods can be employed to evaluate the correspondence between means and process. One of them is the so-called method of expert appraisal. This method is a questionnaire survey of leading scientists in their field pertaining to a specific system, with the aim of determining their view on the possibility of utilizing the given method or means. The second method of appraisal consists in the following: the process of interest and the research means are described in one and the same system of criteria. A comparison of appraisal results can indicate how and to what degree the given means can accomplish the given task -- or on the contrary, what task can be accomplished by the given means.

Obviously the first method -- the method of expert appraisal -- is more subjective than the method of comparison of criteria in one system, and to a certain degree it repeats the method of criteria, since experts, in examining the possibility of accomplishing a given task with the aid of an undersea habitat, cannot help but make a comparative evaluation of the task and the means of accomplishing it. The method of expert appraisal, however, also serves as an indicator of the degree of preparedness of the experts themselves -- leading oceanographers -- to utilize the technical devices of undersea research in the interests of their science.

American scientists from the University of New Hampshire chose the expert appraisal method for evaluating the potential of the undersea habitat as a research device.

Before proceeding with the survey of expert oceanographers and engineers, the survey organizers divided the U.S. continental shelf into regions characterized by comparatively homogeneous water and seabed parameters within their boundaries. A total of six regions -- four in the Atlantic and two in the Pacific -- were designated in U.S. territorial waters and continental shelf.

Then the university scientists sent out a special questionnaire to the most experienced experts in the field of ocean research equipment and methods. The questions contained in this questionnaire pertained to the properties of the water environment in a given region -- state of sea surface, water temperature, depth, current velocities, water clarity -- as well as demands made by scientists on the undersea habitat as a technical device designed for studying these characteristics: depth of habitat submergence, capability of transfer from one site to another, distance between submergence sites, crew size, working time on the seafloor, diver range of operation, etc.

The questionnaires were returned to the university by the surveyed scientists after filling them out; university staff personnel processed them and put together a list of conditions of operation of undersea habitats, conditions of performance of research tasks by the habitat crew and, finally, requirements on the undersea habitats themselves:

working depth: 30 meters, with aquanauts working at depths from 15 to 54 meters;

water temperature: maintaining working efficiency in water at a temperature of 0°C;

state of sea: normal activities in a 4-point swell [rough seas];

mobility: transfer of habitat to new location within 24 hours;

duration of submergence: 14 days;

operating crew: 4 persons.

On the basis of analysis of the returned questionnaires, several types of research activities were determined which, in the opinion of the experts, it is most expedient for aquanauts to perform under water: these include investigation of processes, general survey, and "other" (that is, activities not falling within these groups).

The experts defined investigation of processes as "scientific investigation involving repeated local observations or measurements." These include primarily biological processes, such as reproduction cycles, animal and plant physiology, as well as ecological consequences of pollution.

The term "general survey" encompassed flora and fauna identification and distribution count, study of fish migrations, comparative observation of benthic biological communities before and after the effects of man-caused factors (dredge operations).

The experts included within "other" study of displacement of detritus and unconsolidated sediments, as well as observations pertaining to physical oceanography.

The picture obtained by the scientists at the University of New Hampshire on the basis of the expert evaluation method turned out to be highly approximate. They not only failed to establish a system of selection of research problems for investigation with the aid of the undersea habitat but also simply to determine the place of undersea habitats in the overall arsenal of technical devices for oceanographic research.

Scientists at the USSR Academy of Sciences Institute of Oceanography imeni P. P. Shirshov, evaluating the results of the "Chernomor" program as well as the results of other research programs performed with the aid of undersea habitats, elaborated a system of criteria which characterize both the features of various processes taking place in the sea and the specific characteristics of the undersea habitat as a platform for scientific equipment.

In developing this system of criteria, the assumption was that if the characteristics of a process and a means of research coincide, this process or phenomenon can be studied with the aid of the given technical means.

The method was based on such generalized categories as space and time scales; depth scale; type of information to be collected; nature of processing of information; nature of on-board equipment utilized to study a phenomenon (process).

Each of these categories is divided in turn into smaller ones:

spatial scale -- hundreds of miles, tens of miles, miles, hundreds of meters, tens of meters, meters, decimeters, centimeters, millimeters;

time scale -- processes with a seasonal cycle, daily, hourly, minute, second periodicity, and with frequencies of fractions of a second;

depth scale -- thousands of meters, hundreds of meters, tens of meters, and meters.

This system of criteria presupposes that, depending on the type of information to be collected, the investigator can obtain it either visually (direct observation, photographic recording, TV observation) or by measurements or collecting samples.

Nature of processing information is defined as general visual appraisal, count in situ with equipment (with the aid of microscopes, for example), laboratory analysis (dissection of biological subjects, chemical analysis of water or soil samples, spectrogrammetry, etc), and digital or electronic numerical processing of observation data.

On-board research equipment includes the following: photographic and motion-picture taking equipment, optico-mechanical (binoculars, microscopes), chemical analysis, electromechanical, electronic measuring and electronic computing equipment.

This system of criteria, in the opinion of its authors, can characterize with a sufficient degree of completeness any process or phenomenon in the ocean. For example, if we are speaking about a process possessing spatial scale -- hundreds of miles, a time scale -- seasonal, a depth scale -- thousands of meters, if information on the process can be worked up on shore or on board a ship with the aid of electronic computer hardware, the subject under discussion may be global fluctuations of characteristics of ocean waters.

If a phenomenon possesses a spatial scale -- meters, a time scale -- seasonal, a depth scale -- decimeters above the seafloor, if photographic recording is an available means of collecting information, and general appraisal is the method of processing information, one can assume that what is being studied are fixed benthic biological communities.

This system of criteria also enables one to describe in generalized categories technical means of ocean investigation, whereby each of these means, due to purely technical limitations, will encompass only a certain part of the entire scale of criteria, range of scales and types of information, equipment for information collections, etc. Thus one can come up with a kind of "portrait" of this equipment on the basis of components of this "part" which are characteristic of each technical device. A comparison between the "portrait" of the equipment and a "portrait" of the phenomenon, described in the same categories, will indicate whether a given phenomenon can be studied by a given technical means. If the "portrait" of a piece of equipment is broader than the "portrait" of the phenomenon, this equipment will make it possible thoroughly to study the phenomenon; if the equipment is unable to encompass any aspects of the phenomenon, the phenomenon cannot be studied by means of this equipment.

In principle there are a great many problems which are expediently studied directly in the ocean, and it is practically impossible to list them in a single table. Therefore it was decided to prepare "portraits" for research devices, so that each scientist, in planning his work, can draw up on the basis of this system of criteria a "portrait" of the phenomenon of interest to him and select that research device the "portrait" of which is closest to the "portrait" of the phenomenon.

The proposed system of evaluating research equipment also enables one to accomplish the inverse task. In organizing an expedition based on utilization of a given means of undersea research -- a self-propelled research submarine or stationary undersea habitat, for example -- one can select from the great diversity of proposed scientific problems those which to the greatest degree are in conformity with the specific features, the "portrait" of the given piece of equipment.

And, finally, possessing such a system of objective comparative evaluation of research devices, one could find for each device its place in the overall process of investigation of the ocean.

Table 5 contains one version of description of the principal carriers of oceanographic equipment in a uniform system of criteria. It is evident from the table that each vehicle possesses its own, fairly clearly-marked "portrait." Before beginning analysis of the table, we should like to note that it reflects the potential of a single cycle of utilization of the equipment: one aircraft flight, one buoy station, one research submarine dive. Naturally repeat utilization of equipment platforms substantially broadens their potential. Just what do we have?

Table 5. "Portraits" of Ocean Research Equipment

Parameters of System of Criteria (1)	S (2)	Aircraft (3)	Ship (4)	Buoy Station (5)	UH (6)	RS (7)	RS-D (8)	DB-D (9)	D (10)	RUV (11)
Spatial scale:										
hundreds of miles	+	+	+	-	-	-	-	-	-	-
tens of miles	+	+	+	-	-	+	-	-	-	-
miles	+	+	+	-	-	+	+	-	-	+
hundreds of meters	+	+	+	-	+	+	+	-	+	+
tens of meters	+	+	+	-	+	+	+	+	+	+
meters	-	-	-	+	+	+	+	+	+	+
decimeters	-	-	-	-	+	+	+	+	+	+
centimeters	-	-	-	-	+	-	+	+	+	+
millimeters	-	-	-	-	+	-	+	+	+	+
Time scale:										
season	+	-	+	+	+	-	-	-	-	-
day	+	+	+	+	+	+	-	-	-	-

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
hours	-	+	+	+	+	+	+	+	-	+
minutes	-	-	+	+	+	+	+	+	+	+
seconds	-	-	+	+	+	+	+	+	+	+
fractions of a second	-	-	+	+	+	+	+	+	+	-
Depth scale: thousands of meters	-	-	+	+	-	+	-	-	-	+
hundreds of meters	-	-	+	+	+	+	+	+	-	+
tens of meters	+	+	+	+	+	+	+	+	+	+
meters	+	+	+	+	+	+	+	+	+	+
Type of information: visual	+	+	-	-	+	+	+	+	+	+
samples (measurements) fixed in situ	-	-	-	-	+	+	+	+	+	-
samples (measurements) with isobaric processing	-	-	-	-	+	-	-	-	-	-
samples (measurements) with processing on the surface	+	+	+	+	+	+	+	+	+	+
Nature of processing: general visual appraisal	+	+	-	-	+	+	+	+	+	+
laboratory analysis (microscope, dissection, chemical analysis)	-	-	+	-	+	-	-	-	-	-
digital and computer processing	+	+	+	+	+	+	+	-	-	-
Nature of on-board equipment: photographic	+	+	+	+	+	+	+	+	+	+

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
optico-mechanical	+	+	+	+	+	+	+	-	-	-
chemical analysis	-	-	+	-	+	-	-	-	-	-
electro-mechanical	-	-	+	+	+	+	+	-	-	+
electronic measuring	+	+	+	+	+	+	+	-	-	+
electronic computing	+	+	+	-	+	+	+	-	-	-

Note: S -- satellite; UH -- undersea (manned) habitat; RS -- research (manned) submarine; RS-D -- research submarine with diving compartment; DB-D -- diving bell with diver water exit; D -- diver descending from surface; RUV -- remote-controlled undersea vehicle.

From the standpoint of spatial scale, those devices which do not provide direct contact between scientist and object of investigation are effective in studying large-scale phenomena, while devices which provide such contact are effective in studying small-scale processes.

On a time scale oceanographic vessels and stationary research facilities -- buoy stations and undersea habitats -- have the broadest range. Means of non-contact study of the ocean -- satellites and aircraft -- are most effective in studying slowly-changing processes in the ocean, while undersea research equipment is effective for studying high-frequency processes.

All ocean research equipment and facilities also divide into three groups according to depth scale. Means of noncontact study of the ocean -- aircraft and satellites -- "look through" only the surface water layers. Oceanographic vessels, buoy stations and undersea habitats are effective throughout the entire range of ocean depths, right down to extreme depths. All research equipment based on utilization of diver labor (with the exception of free dive from the surface) can be employed to depths of several hundred meters.

As for type of collected information and the nature of its processing, undersea habitats possess the greatest potential, while the least is possessed by buoy stations and divers diving from the surface.

Oceanographic vessels and undersea habitats can carry the maximum volume of on-board equipment, while divers carry the minimum volume of equipment.

An analysis of Table 5 can provide a basis for a number of conclusions and recommendations. For example, first of all it is evident that all devices permitting man to penetrate under the water provide the capability to conduct investigations of small-scale high-frequency processes with coordinated tie-in to base readout facilities.

Secondly, all equipment permitting man to get out into the water are limited in utilization depth.

Further, all technical devices which enable man to work under water provide the possibility of observing and processing an object directly in the water, in minimally disturbed environmental conditions.

And finally, it is evident from the table that the closest analog of the oceanographic vessel as regards capabilities for employment of research equipment is the undersea habitat.

Summarizing the commentary to Table 5, one can state that employment of undersea habitats in oceanographic research is expedient from a methodological point of view in studying local processes throughout the entire range of frequencies if the nature of the investigations requires a precise spatial tie-in of performed measurements and extensive utilization of laboratory equipment for analysis of an object with minimum environment disturbances. This essentially means that a given task, which corresponds to the formulated conditions, cannot be accomplished with the aid of other technical means.

There also exist other tasks which cannot be accomplished by traditional means, that is, with the aid of oceanographic vessels. For example, effect of gale-driven swell on the underwater environment -- such as the specific features of lithodynamic processes under gale conditions or the influence of gale-caused water turbidity on fish behavior.

Data of this nature can be collected only by divers, working out of an undersea habitat, which is sited at a depth reached by gale-driven swell in attenuated form.

There are, however, a number of tasks which can be accomplished not by one but by several types of technical devices. In this case not methodological but rather technical-economic considerations come into play in selecting means of investigation. For example, if the research task requires employment of a substantial volume of diver work to obtain purely visual information, the question of selecting a technical means of investigation -- undersea habitat, vessel with diving equipment, or simply a diver descending from the surface -- is settled from the position of organizational or economic expediency.

To demonstrate that scientific investigations conducted from undersea habitats are more effective than investigations performed by sending down a diver from the surface, one can cite the conclusion reached by investigators working with both methods.

"Employment of an undersea habitat (decompression is not needed)," wrote ichthyologists of the U.S. Government Bureau of Commercial Fisheries after working on one of the Tektite teams, "and closed-cycle breathing apparatus (does not produce bubbles) enabled us in 17 days (100 hours of work in the water, two persons) to collect so much data that the volume can be compared with data obtained by Hobson as a result of working under water for 1200 hours, or with data obtained by Stark and Davis as a result of 100 night dives and an even larger number of daytime dives."

And finally, there is a third kind of task for the purposeful performance of which utilization of undersea habitats is inefficient, since it is dictated neither by methodological nor economic necessity -- for example, operation of a standard hydrological station without special restrictions on method of measurements. It is true that in a number of instances these tasks have also been included in the activities programs of habitat teams, but they have been of a subordinate nature and served only to supplement the measurements and investigations performed in the basic program, such as recording the background against which a specific target process takes place.

Thus undersea habitat teams can state specific oceanographic research, performance of which is impossible with the aid of a given technical device; nonspecific tasks which, although they can be performed by many investigative means, the optimal facility is the undersea habitat and, finally, nonspecific investigations supplementing the main work program.

Receiving task evaluation criteria from the standpoint of possibility and effectiveness of performance with the aid of an undersea habitat, one can proceed to scientific program formulation proper.

There are a great many possible variant scientific work programs, but on the whole these programs are formed, from the standpoint of occupation of the habitat team, of tasks of two types. In one case aquanauts perform instrument, quantitative measurements, and in another -- visual, qualitative observations.

"Chernomor" and Sealab hydrophysical activities can serve as an example of instrument measurements; the same applies to studies of distribution and composition of plankton in the Tektite and Hydrolab programs; experiments in hydrochemistry, etc. These measurements are characterized by a comparatively low degree of aquanaut work occupation outside the habitat, in the water, and a large volume of analytical work directly in the habitat.

As regards visual, qualitative observations, a large volume of purely diver activities is typical of them -- and comparatively little crew activity in the habitat itself.

Experience in operating undersea habitats, including the "Chernomor-2m" undersea laboratory, has shown that a scientific program combining both instrument measurements and visual observations, tasks requiring both aquanaut work inside the habitat and extended excursions into the water, can be optimal. Thus an instrument hydrooptical program and visual, qualitative investigations of lithodynamic processes were combined in the "Chernomor" program.

There is one more specific element which is desirable to consider in drawing up a work program -- it is the interrelated nature of the areas being elaborated. The instrument and "visual" portions of programs can be selected in such a manner that they are not completely independent but "work" on one another.

For example, a hydrochemical program, constituting an end in itself, at the same time can provide a background picture for biologists. Such an interlink between programs not only increases the effectiveness of activities in each program section but also improves the morale "atmosphere" on the habitat team -- which we shall discuss in detail below.

Thu we have found a mode of selecting from the entire diversity of tasks those which can be accomplished solely -- or most efficiently -- by the crew of an undersea habitat. We have learned to put together combined, mutually supplementing research programs, providing a uniform work loading on crew members. But this program and these investigations are local -- they extend out only several hundred meters -- the range of action of the aquanaut.

In order better to understand the substance of the obtained data, to interpret them better, it is advisable concomitantly with undersea habitat activities, to record the background in the area where the investigations are conducted. This background can be surveyed by surface vessels with the aid of traditional methods of investigation or even with the aid of satellites and aircraft, as was done in the Tektite experiment.

Thus the aggregate of technical devices investigating the selected area broadens. It includes an undersea habitat with power buoy and scientific support vessel. The habitat is sited in the zone of maximum gradients of the target phenomenon, and then the scientific support vessel begins performing background investigations within a radius of 100-200 miles from the habitat site, maintaining continuous radio contact with the habitat. Upon completion of its activities the habitat surfaces, summons the scientific support vessel, and the entire group proceeds to a new research area.

Aquanaut-Oceanographers

Successful performance of a work program by a habitat team depends not only on how thoroughly thought through and carefully selected are the scientific tasks of the experiments and how well the investigation process proper is organized. Also of great importance is selection of team personnel. A felicitous selection of team members does much to improve the psychological and emotional stability of the group, its working efficiency and effectiveness.

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APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000300020041-1

The question of personnel selection for an isolated group and the dynamics of relationships within the group and between the group and support services has not yet been adequately studied. In addition, the majority of studies conducted in this area pertained to groups with strong formal ties (discipline, military subordination, etc), such as submarine crews.

The crew of an undersea habitat is to a certain degree untypical in makeup and principle of selection. Since the main task of the aquanauts is to perform scientific investigations, a habitat team includes scientists of the most diverse areas of specialization, who as a rule are not previously linked together by subordination relations. Under these conditions the stability of interrelationships within the habitat team depends directly on the degree of motivation of the team members. This element is particularly important since scientists, persons with a highly-developed intellect, are as a rule distinguished by an informal approach to problems which arise at any level, including problems connected with crew internal routine. The crew's work will proceed without complications only if each member of the team is very sure of the necessity for a given action.

As a rule selecting undersea habitat team personnel takes place in several stages. Usually the first thing to be determined is the areas of specialization of the personnel to take part in the experiment.

With the current technical and organizational level of work and research involving undersea habitats, as a rule the habitat team consists of an operations and maintenance group and a scientific group. The job of the operations and maintenance group is to ensure failure-free operation of habitat systems and to create the conditions required for performance of scientific investigation. The principal objective of the scientific group is to perform research proper.

As already stated, development of research techniques involving employment of undersea habitats aims at establishment of self-contained undersea complexes the work performed by which is independent of surface support services, at any rate in organization of crew living routine, work routine, and equipment operation. This condition automatically involves, independent of the nature of the scientific program, inclusion of two specialization areas within the operation and maintenance group of specialists: an on-board engineer and a doctor specializing in physiology.

The engineer's functions include routine servicing, maintenance and repair of habitat equipment; the physiology specialist's job involves regular monitoring of the crew's state of health.

In practical work activities with the "Chernomor" undersea habitat, the crew included an additional member, regardless of the nature of research being performed -- a diving expert. The need for his participation in crew activities was dictated by the fact that aquanaut extravehicular work activities require special care in preparing gear and observing diving rules and regulations.

Scientific group personnel are usually selected with consideration of the research program. It includes specialists in the main and supplementary programs, and as a rule each part of the program is represented by one specialist. In addition, the scientific group includes one or two professional divers, including a habitat diving expert.

Thus the habitat crew usually consists of 5-6 persons divided into two groups, the principal interests of whom generally differ.

As a rule the scientific group endeavors to collect as much material as possible, and sometimes scientists, carried away by the process of investigation, are willing to make departures both from the crew's scheduled daily routine and in some measure from the demands of diving safety. The operation and maintenance group, on the contrary, endeavors to ensure mishap-free crew activities, sometimes to the detriment of the scientific program. This difference in objectives, possibly unrealized and subconscious, nevertheless affects the crew's working efficiency and may also be a direct source of conflicts.

In the Tektite II program series of submergences, for example, both scientists and engineers were placed in command of teams of aquanauts. Analysis of team activities indicated that in the former case a team works more purposefully and devotes more time to investigations than if the team is led by the crew engineer.

An extremely important factor which determines the overall psychological "mood" of the crew is complete respect for the duties of one's fellow crew members. The experience of numerous habitat missions indicates that crew work productivity increases if all members participate together in the work to one degree or another, assisting one another, even if this goes beyond the prescribed boundaries.

After crew selection "by areas of specialization," in conformity with the scientific program, it comes time to make the personal selection of crew members.

Up to the present time there is no rigorous method of selecting persons for isolated groups, especially taking into account the dynamics of relationships within a group.

As a rule psychophysiological investigations have included collection of sociological data, performance of psychomotor tests, testing of eyesight and hearing, etc. However, in choosing candidates for a habitat crew one should take into account in addition a number of objective and subjective indicators, and while a system of objective criteria has been created for selecting aquanauts on the basis of state of health, there is at the present time no method of psychophysiological crew member selection. At the present time the question of selecting a crew member candidate is determined by evaluation of the candidate's professional qualities, while a conclusion on the psychophysiological compatibility of crew members is made on the basis of the intuition of the physiologist and work supervisor. Field studies in the area of psychophysiology of aquanaut teams spending extended periods of time under pressure has essentially just begun. American psychologists studied this problem on the Sealab II and Tektite teams. Similar studies were conducted on the "Chernomor" program.

A comparatively small volume of selected information does not yet enable investigators to create a scientifically substantiated methodology of selecting crew candidates, but some preliminary recommendations have been formulated.

For example, by the expert appraisal method it has been possible to determine those personal qualities of aquanauts which seem most valuable for working together with others in an undersea habitat. U.S. aquanauts -- participants in the Sealab program -- listed these qualities as follows, in descending order of importance: diving experience; conscientiousness in doing one's share of the common job; professional training; physical training; sense of humor; well-developed imagination; efficiency; gives moral support to comrades; tactfulness; enthusiasm about one's job; purposefulness; ability to concentrate on one's work; prior work experience with the same crew; ability to inspire frankness; lack of excessive reserve; age.

Of course demands on an aquanaut are not limited to this list. One can, however, attempt to formulate demands on the aquanaut-investigator at least in a general way. In the opinion of U.S. experts, demands may be as follows: "An aquanaut is distinguished by the ability to live and work at great depths for an extended period of time; to service and maintain undersea habitat equipment and systems, and to utilize deep-water diving gear... possesses knowledge in biology and general oceanography."

In addition to the above, there is one more demand which the aquanaut-oceanographer should meet: a high degree of professional training as a scientist and a capability for independent research work.

Our Home Is An Undersea Habitat

Organization of experimental research in the sea is no simple task, particularly if an undersea habitat is being utilized. The primary difficulty is that the method of investigation of the ocean with employment of manned undersea facilities is too young -- slightly more than 15 years old, and the basic organizational solutions and principles have not yet been "solidified." In view of this fact, an analysis of methodological, technical and organizational experience amassed up to the present time is highly desirable, since it is precisely the organizational arrangement which in the final analysis also determines concrete design decisions.

Conduct of research under water from an undersea habitat is based on utilization of an entire aggregate of underwater and surface equipment. The relative share of participation by underwater and surface facilities in conduct of an experiment may vary in relation to design and structure of the habitat. Obviously the more self-contained an undersea habitat is in its operation, the less it needs technical support from the surface, and vice versa.

The correlation between the capabilities of a habitat proper and its requirements in continuous technical support from the surface very substantially influences the reliability of the entire course of research investigations. There have been many cases in world oceanographic practice where an experiment has been forced to terminate ahead of schedule because habitat technical servicing was made impossible due to surface weather conditions.

It would be useful for us to discuss two extreme instances as an example of work organization -- the Tektite and ("Idzher") programs.

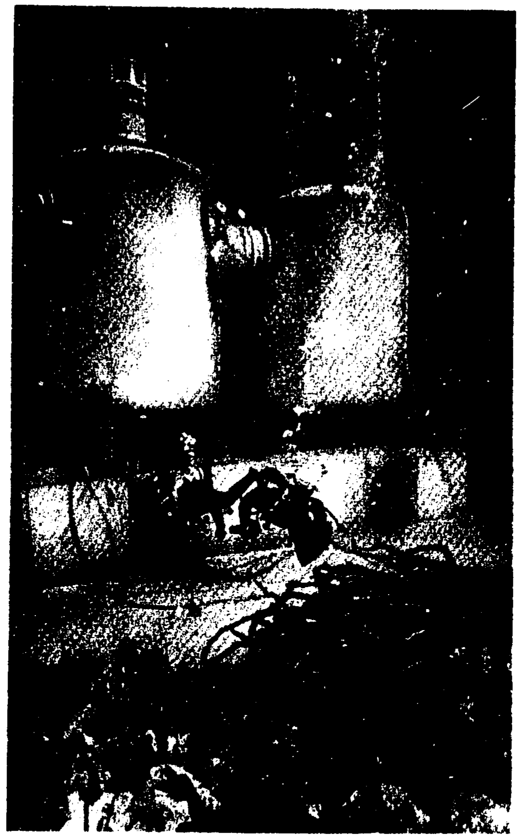
The Tektite program was organized by the U.S. NOAA with the participation of a number of U.S. Government agencies, including the Navy. Naval experts who had participated in the Sealab program were enlisted to carry out this program, which determined the general structure of organization of the experiment and, consequently, design of the habitat itself.

The Tektite habitat is a stationary undersea manned structure designed for life support and work at a depth of 15 meters for a 5-man crew breathing an artificial atmosphere at a pressure equal to that of the water around the habitat.

The habitat does not possess surface navigation capability, and therefore it was delivered to the submergence site by floating dock. The habitat is not capable of independent submergence and surfacing; these operations were performed manually, by divers working with underwater winches. The habitat hull was not strong enough so that an interior pressure could be maintained at the sea's surface equal to water pressure at the working depth, and therefore a shipboard diving unit was employed to evacuate the crew from the habitat -- a deck decompression chamber and a diving bell -- accommodated on a barge 15 meters in length and 7.5 meters in beam.

Due to the fact that the habitat does not carry on board its own supply of compressed gases, fresh water and power supply, it was necessary to place on station above it an additional barge carrying compressors, a diesel generator, and tanks of fresh water; the barge was 15.7 meters in length and 6.5 meters in beam.

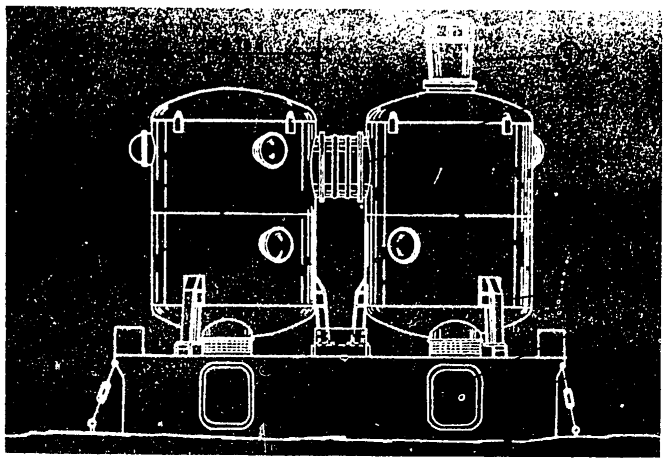
Habitat work operations were directly supported by 40 oceanographers and approximately 30 engineers and technicians. In order to provide them with normal living and working conditions, a camp was set up on shore, with camp services employing an additional 46 persons. Thus to support five aquanauts it was necessary to enlist more than 100 persons and two equipment-carrying barges, which sharply reduced the aquanauts' work efficiency.



Tektite undersea habitat. The habitat's design makes its employment in open-sea conditions impossible.

The approach to the ("Idzher") program was directly the opposite. The organizational structure was based on the principle of maximum self-sufficiency and independence of laboratory work operations from surface support services. At all stages of the ("Idzher") undersea habitat operation the total number of service personnel did not exceed 150, and they were deployed on a vessel displacing slightly more than 100 tons.

The design features of this habitat enabled it to be towed in a 6-point swell [high seas]. It could dive to the seafloor and surface independently, without surface support vessels; the design of the habitat's pressure hull



Schematic Diagram of Tektite Habitat.

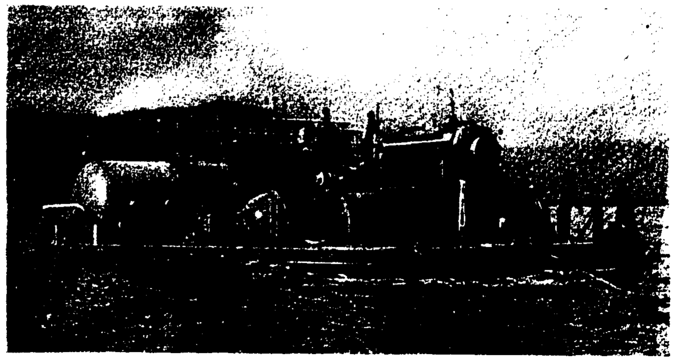
Key:

1. Platform
2. Entrance
3. Hull support
4. Hull
5. Viewing port
6. Diving compartment
7. Habitat systems compartment
8. Connecting tunnel
9. Observation dome
10. Laboratory section
11. Sleeping quarters
12. Seafloor

made possible crew decompression and medical recompression on the surface, in any of its three compartments.

Experience in organizing operations with the ("Idzher") undersea habitat was further pursued in subsequent Hydrolab, "Helgoland," and PRINUL program experiments. At the present time this undersea research support arrangement is as follows.

A manned undersea habitat adapted for operation in the open sea forms the basis of the complex of equipment and facilities. The habitat is towed to the submergence site or to port. Its systems are designed so that all routine servicing and maintenance is handled by the habitat team members, without involvement of surface personnel. Stores of compressed gases, electric power and fresh water, consumed during the course of habitat operations, are replenished from an automated unmanned power buoy (also a component of the complex), which is located on the surface, above the submergence site.



The ("Idzher") undersea habitat can be towed in a 6-point swell, and can dive to the seafloor and surface without the assistance of support vessels.

Such an arrangement greatly simplifies work organization and decreases the number of auxiliary personnel and fleet, thus reducing the cost of operations and increasing their efficiency.

At the same time, in organizing an experiment one should also bear in mind the specific working aspects of the aggregate, and chiefly of the undersea habitat as a base for conduct of scientific investigations. A habitat should introduce minimum disturbances to the environment, be it sound, light, release of organic substances, etc; the interior spaces -- the compartments, should be suited for the performance of scientific work.

Thus we have the habitat as an underwater structure providing life support and supporting crew health, and the habitat as a base for undersea research.

The entire operation of performing research tasks with the aid of an undersea habitat can be divided into a number of stages: travel to the work site and return to base; submergence to the seafloor; moving into the habitat; underwater work proper; crew decompression; surfacing the habitat.

Travel to the work site is performed either with the assistance of some transporting carrier vehicle or by towing afloat by a support vessel or, finally, under the habitat's own power.

Travel to the submergence site on the deck of a support vessel was employed in the Sealab I, Tektite I, II, "Meduza" and other experiments. This method of transport does not require navigation capability of the habitat proper, although it sharply limits its displacement, which is directly dependent on the load-hoisting equipment of the support complex. Today this method of transport has been practically abandoned.

Towing undersea habitats afloat has been most frequently utilized in world practice. This method of transport imposes certain demands on the design and construction of the habitat proper. It should be sufficiently seaworthy, that is, possess good stability, reserve buoyancy, and tow capability. Disregard of these qualities can lead to loss of the habitat even before the project begins, as was the case of the "Permon-2" habitat.

Not one of the existing undersea habitat designs is capable of independent travel to the work site. The American "Diver Boat," which is presently on the drawing board, is an exception. However, the question of whether a habitat should definitely be self-propelled remains open at present, since this capability greatly complicates and increases the cost of habitat design and construction, increases crew size and operating cost, although the time during which it is en route to the site is considerably less than the time it spends under water.

Evidently for the present time the optimal mode of habitat travel to the work site is towing afloat.

Habitats submerge to the seabed in four ways.

In the first two experiments (Sealab I, for example), the cargo-hoisting equipment of the floating support bases were employed. Habitats submerging in this manner lack their own water ballast systems, which means simplicity of design. The need for powerful hoist equipment on support vessels, however, and the dependence of the submergence process on weather make utilization of this method highly undesirable.

Another method is submergence with the aid of a built-in or seafloor winch. The habitat hull, possessing positive buoyancy, is connected by cable to an anchor lying on the seafloor and weighing more than the hull's positive buoyancy. The cable is reeled in by a winch mounted on the anchor or in the habitat hull, and the hull is drawn toward the seabed. This method was used to submerge the "Caribe", BACH-2, and "Meduza-1, 2."

Another method that began to be practiced was habitat free dive under the effect of forces of negative buoyancy. An undersea habitat capable of submerging with this principle contains its own water ballast system (in many respects similar to the ballast system of submarines), which enables it to change buoyancy from positive to negative. In designing this system, however, one should also bear in mind the necessity of submerging the habitat and placing it on the seabed at the desired location, and securely anchoring it on the seafloor during habitat operations -- for weeks and even months.

An intermediate method of habitat submergence is also fairly extensively employed. The habitat possesses negative buoyancy due to its water ballast system, but its rate of dive is controlled by support vessel winches or cranes. Precontinent-3 and Sealab II and III were lowered to the seabed in this manner. This method of submergence, however, combines the drawbacks of both above-described submergence methods. The fact that the habitat contains its own water ballast system complicates its design, but it is unable to dive independently and consequently requires the availability of hoist equipment on board support vessels; in addition, this method makes submergence dependent on weather. Therefore evidently the free-dive method is the most preferable method of placing a habitat on the seafloor.

Undersea habitat initial occupancy would be effected by the crew free-diving from the surface to the habitat, placed in advance on the seabed, by going down in a diving bell, with preliminary compression in the support vessel's shipboard pressure chamber, and crew submergence directly in the habitat itself.

The method of crew free diving from the surface is the simplest, but capabilities are limited to depths from which an aquanaut can return to the surface in case it proves impossible to enter the habitat immediately. Evidently depths of 30-40 meters are entirely reasonable for this method of "moving into" a habitat, although it is hazardous to utilize this method at greater depths, since duration of decompression with forced return to the surface may exceed the diver's physical capabilities.

A habitat crew can be delivered to depths of above 30-40 meters in a diving bell. The advantage of this method lies in the fact that the diver who readies the habitat for occupancy has a secure avenue of retreat -- in case of delay he can immediately withdraw into the waiting diving bell. One of the two divers who were readying Sealab III for occupancy was rescued precisely due to the diving bell. Even this method, however, has its drawback -- a special diving tender with pressure chamber unit on board must be maintained above the habitat submergence site until the crew takes up residence, and this of course greatly complicates conduct of the entire operation.

The method of descending the crew in the habitat itself is extensively employed. In this case the crew members take their places in the compartments prior to submergence, after which breathing mixture pressure in the pressurized compartment is raised to working pressure and the crew takes the habitat to the seabed. Crew compression in and descent with the habitat sharply reduce the volume of surface support required for placing the habitat onto the seafloor. In combination with free dive by the habitat itself, this method of putting the crew on board makes the process of submergence practically independent of supporting equipment and facilities at all stages.

One drawback of this method, however, is the fact that during descent -- and emergency situations occur most frequently precisely during this phase -- the crew, which is on board the habitat, is subjected to all the vicissitudes of its fate.

Obviously one cannot give unequivocal recommendations on method of tenanting a habitat -- everything depends on the conditions of job performance. Nevertheless one can assume that with increasing overall independence of habitats from surface support facilities, and especially as habitat submergence depths increase, putting crews under water directly in the habitat compartments will become increasingly a preferred procedure.

A habitat crew may remain weeks or months on the seafloor. During this entire time forces generated by motion of seabed-adjacent water masses are acting on the habitat hull. Therefore, in order to avoid any habitat movements or impacts against the seafloor, it is essential to secure it firmly to the seabed.

Up to the present time three methods have been employed to secure habitats to the seafloor: securement by anchors, pressing the habitat firmly against the seafloor with additional solid ballast, or filling a special anchoring ballast tank with water.

With the first method the habitat hull, which has certain positive buoyancy, is secured to anchors which are positioned in advance or lowered onto the seafloor. This method, however, provides limited holding force, for the weight of the anchors is determined by the capacity of the hoist equipment of the habitat proper, which carries these anchors, or of the surface support facilities. The "Caribe," "Meduza-1, -2," and BACH-2 habitats were anchored in this manner.

When anchoring with solid ballast, ballast is loaded into the habitat's bunkers after it is placed onto the seafloor, until the desired negative buoyancy is achieved. This method was used to anchor the "Sea Star" (Precontinent-2), Sealab I, and "Glaucous" habitats. This method contains two drawbacks -- the need to employ divers to load and unload ballast and the impossibility of a rapid emergency surfacing of the habitat.

The most extensively employed is the third method of anchoring a habitat on the seafloor -- with the aid of water-filled anchoring ballast tanks, which increase its negative buoyancy on the seafloor. This technique was employed to anchor Precontinent-3, Sealab III, ("Idzher"), "Helgoland," "Chernomor," etc. This method requires neither utilization of diver labor nor preliminary equipping of the seafloor at the submergence site and permits the habitat to surface rapidly in case of need. Evidently preference in the future will be given precisely to this method.

Mishap-free habitat operations on the seafloor are determined not only by the technical perfection of its systems but also by the degree of its dependence on surface or shore support facilities, that is, its self-sufficiency. There have been many cases where inadequate habitat self-sufficiency with forced termination of surface support has led to termination of habitat operations.

Capability of self-contained, self-sufficient operations is a highly desirable quality of the habitat, but the present level of technology permits complete habitat self-sufficiency only as regards breathing mixture, means of regeneration, food and water supply. An on-board power supply as a rule provides only limited self-sufficiency of habitat operation. The optimal solution would be an on-board power supply which would permit laboratory operations for a time sufficient to find and correct the cause of interruption of power supply from the surface or, if this is impossible, to perform complete crew decompression procedures prior to surfacing. Proceeding from these requirements, a habitat should be able to operate for 7-10 days on its own power supply.

Decompression, a procedure which a habitat crew should go through prior to surfacing following an extended stay under water, is also an important aspect of undersea research activities. Decompression time can be approximately figured at 1 hour for every 1.5-2 meters of depth. Decompression from a depth of 30 meters, for example, will take approximately 24 hours, more than 40 hours from 60 meters, and approximately 70 hours from 100 meters. In any of these cases the decompression process is fairly lengthy, and during all this time the crew should remain in conditions of comfort and safety. Precisely safety and comfort are the principal factors determining the validity of a given mode of decompression, and consequently the method of crew recovery from the seafloor.

Up to the present time aquanaut decompression has been performed with four methods. The first method involves bringing the crew up to the surface together with the habitat, maintaining equality of pressure of the breathing mixture in the compartments and external water pressure. Pressure in the habitat compartments drops as the habitat rises, and the crew decompresses. The habitat hull need not be hermetically sealed; rate of ascent is controlled by surface hoist equipment. This method is hardly ever employed today because of its poor degree of reliability.

The second method involves bringing aquanauts to the surface in a diving bell with subsequent decompression in a shipboard pressure chamber. This method is employed for the most part in U.S. experiments involving extended stays by personnel under water: the Sealab and Tektite programs. This method of personnel recovery is very convenient when there is an extended stay in the habitat, since it makes it possible to change crews without bringing the habitat itself to the surface.

A third method involves lowering the breathing mixture pressure in the habitat compartments after it surfaces, with pressure in the compartments equal to pressure at the working depth. This method was used to decompress the crews of Precontinent-3, ("Idzher"), "Chernomor," and a number of others. This method is perhaps one of the most convenient and least hazardous for the crew.

A fourth method, which also seems quite promising, came into use quite recently. This method involves decompression on the seafloor in the habitat, with subsequent surfacing of the habitat, carrying the crew up. This method was used to decompress the crew of the "Helgoland." This method involved a number of organizational difficulties, but it will probably be extensively utilized in areas with harsh weather conditions.

The method of raising a habitat to the surface is determined to a substantial degree by the method of placing it on the seafloor. Raising a habitat with the aid of the hoist equipment of surface support vessels (experiments of the Sealab series) is the most laborious and is dependent on weather conditions. The most common is the method of habitat free surfacing by blowing the water ballast tanks with compressed air (Precontinent-3, Chernomor, and other experiments). This method of surfacing seems optimal at the present time.

Analysis of the conditions of operation of habitats and the circumstances of mishaps which have occurred with them suggest the following conclusion: it is desirable that a habitat be seaworthy, be capable of descending to the seafloor independently, without the assistance of surface support facilities, and also be capable of surfacing independently. It is very important that habitats possess a pressure hull which provides capability to decompress the crew both on the top, after surfacing, and on the bottom, prior to surfacing. It is essential that on-board stores of compressed gases, food, water, means of breathing mixture regeneration, and power provide self-contained operation of an undersea habitat for at least 7-10 days.

With further detailing of desirable qualities of undersea habitats, the following "ideal" picture of an undersea habitat emerges.

Seaworthiness qualities enable a habitat both to be towed on the surface and to move independently -- both on the surface and under water.

Hull design provides capability for crew decompression both on the bottom, prior to surfacing (medical recompression capability on board) and on the surface, if weather conditions permit, for example (the habitat contains a surfacing shelter-compartment which is self-contained in all systems and equal in hull strength to the main compartment; an airlocking system is provided, for moving personnel and equipment into the compartment with decompression on the surface). The hull is also adapted for crew recovery from the seafloor by means of "dry" docking with a diving bell.

The systems providing habitability of an undersea habitat permit adjustment of the composition of the artificial breathing mixture and its closed-cycle regeneration, plus control of the temperature and humidity of this mixture. The habitat is equipped with a galley, shower, and toilet facilities.

Ballast systems provide capability to submerge and surface the habitat without the assistance of surface support facilities, to work on the seafloor in difficult conditions (current, gale-driven swell, etc), and immediate emergency surfacing.

The habitat is self-sufficient in food and water; in means of breathing mixture regeneration and gases -- breathing mixture components and gases for diver breathing during outside-habitat activities; process water and process gases (for pressurizing fresh-water tanks, blowing ballast tanks, etc) for the entire duration of the mission; a 7-10 day power supply.

We can evidently assume that the present level of technology permits design and construction of an undersea habitat which is capable of withstanding conditions of operation in the open sea. As we have already stated, however, an undersea habitat proper is only a part of a complex, which also includes an energy buoy anchored on the surface above the habitat, supplying its systems with compressed gases, electric power, and fresh water.

At the present time there exist only three power buoy versions: those of the "Helgoland," Hydrolab, and "La Chalupa" habitats. Experience in operating these buoys, however, enables us to present several recommendations of a general nature.

A power buoy should be an all-weather floating device, that is, should maintain the operating capability and efficiency of all equipment across a broad range of weather and sea conditions. It is evidently simpler to ensure the unsinkability of the buoy than to secure reliable equipment operation. In spite of a rigid testing program for the "Helgoland" habitat power buoy, for example, during which equipment was subjected to 45° amplitude pitching, during operation there frequently occurred interruptions in the "Helgoland" power supply because the diesel fuel system would become fouled with dirt raised from the bottom of the fuel tank during power buoy rolling and pitching in the swell.

In addition to auxiliary equipment supporting operations of an undersea habitat -- diesel generator, diesel compressor, water pumps, batteries of tanks with an emergency supply of compressed gases, etc -- a power buoy should also carry mooring and anchor devices, plus marker lights.

For the oceanographer comfort and safety are an essential condition, but this is not the main thing for the sake of which he submerges to the seabed. The main thing is effective, efficient research work under water.

What features should an undersea habitat possess in order to ensure this effectiveness?

Experience of operating undersea oceanographic habitats has shown that the success of scientific investigations depends to a significant degree on to what extent the habitat is suited to the conduct of research, and therefore no less importance should be attached to equipping compartments designed for scientific work than to living quarters or diving compartments.

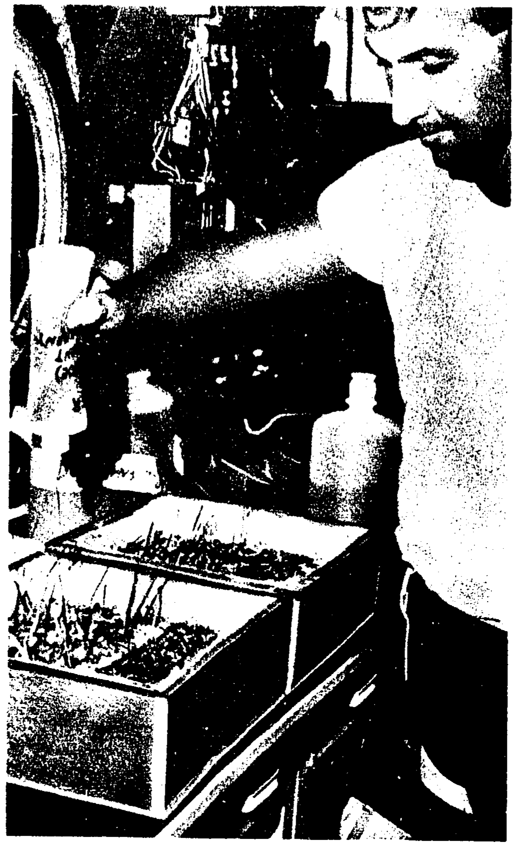
Laboratory compartment of Tektite undersea habitat. Parameters of the gas medium in the compartment permit operation of complex electronic measuring equipment.

The optimal laboratory compartment is set up approximately as follows. It has soundproof walls and ceiling. The parameters of the compartment's microclimate -- temperature and humidity -- ensure reliable electronic equipment operation. Each aquanaut-researcher work station is equipped with a work table or desk with adjustable local lighting, air purification system intake, and communications system microphone and telephone. The compartment contains viewing ports for direct observation of the external environment, a washbasin with hot and cold running water, a refrigerator for storing reagents and samples, and racks for scientific equipment and collected specimens. There is a direct exit from the compartment into the diving compartment.

Of all the presently-existing undersea habitats, the laboratory compartment of the "La Chalupa" habitat meets the above-listed requirements to the greatest degree.

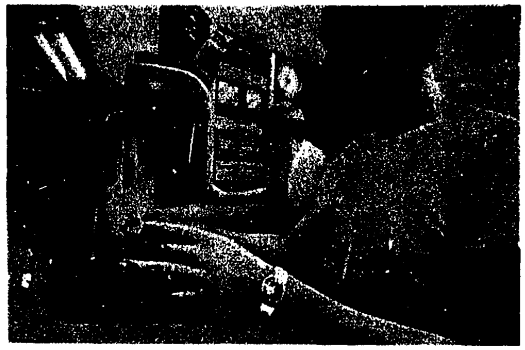
What kind of equipment can be installed in the laboratory compartment? Even a brief list of instruments which have been utilized in undersea experiments can give a fairly accurate picture.

The following have been utilized in undersea habitats: binocular magnifying glasses, microscopes, equipment for titrating samples, aquariums with circulating water, tape recorders, recording potentiometers, electronic measuring units, photomultipliers, high-voltage rectifiers, gas chromatographs, mass spectrographs, etc.



Experiment in growing vegetables in the helium-oxygen environment of the Sealab II habitat, sited at a depth of 60 meters.

An appraisal of current trends in design of underwater habitats and support equipment and facilities indicates that the undersea habitat and its auxiliary equipment should be viewed as a single inseparable aggregate of technical devices. (For example, a power buoy, which floats on the surface above an undersea habitat, plays its part in conduct of an underwater experiment program. The buoy contains not only equipment for crews to communicate with support services but also various equipment for collecting, primary processing and transmission of data by radio channel to a computer on board the support vessel or on shore). This entire aggregate should be designed specifically taking into account the mission at hand -- investigation



Optico-mechanical instruments have been extensively employed in the research activities of aquanaut-biologists.

of the ocean, and the degree of conformity between the parameters of this complex and the mission to be accomplished determines its effectiveness as a means of oceanographic research.

Arsenal of the Aquanaut-Oceanographer

The great diversity of phenomena and processes studied by aquanauts also dictates the diversity of the techniques of organization of investigations utilized by them. An aquanaut residing in an undersea habitat is no longer a brief-duration guest on the seafloor; he is working in the water continuously, day after day, several hours at a time. He has the opportunity -- and the necessity -- not simply to conduct observations but to organize his work station, the target area or object in such a manner that his work produces the greatest effect. The aquanaut creates a unique underwater testing ground in which he can perform the required experiments over the course of weeks and months.

Such experiment areas, depending on the aims of the investigations, can be quite diversified: geological, biological, hydrophysical, etc.

What determines, however, the necessity of setting up a research area and its structure? First of all it is of course the task proper: conduct of extended observations in the given area under specially organized and monitored conditions, and the nature of these observations.

Naturally a biological experiment area differs greatly from a geological. In addition, even within a single discipline, geology, for example, experiment areas may be totally unlike one another in equipment setup and composition. But nevertheless they contain a number of common features, which enables us to digress from the specific function of an experiment area and to give them a general evaluation.

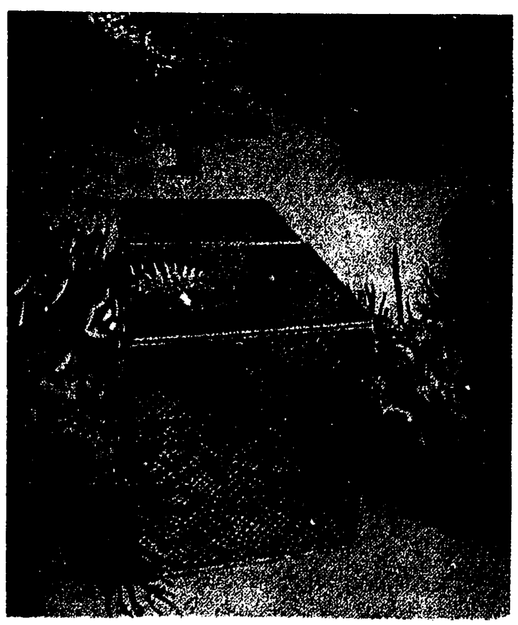
APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000300020041-1

The simplest kind of experiment area is one intended for supplementary visual observation of processes which take place in natural or artificially organized missions.

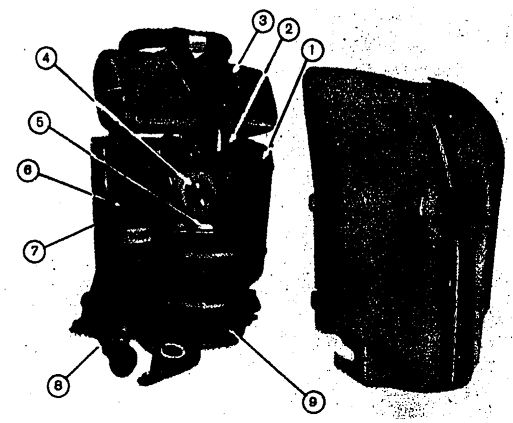
Such observations may include, for example, observations of the behavioral reactions of biological subjects. Research areas for investigations of this type are equipped with shelters for aquanaut-observers, and sources of stimuli of various types (noise, light); artificial micro- and mesotopographic seabed forms are created in these areas (for example, man-made reefs, refuges for fish), etc.

Research areas of the second type are for studying phenomena the nature of which requires only periodic aquanaut visits to the area to collect samples, take measurements, photograph, etc. Geological research areas can serve as examples.

And finally, if the nature of a phenomenon permits its investigation without the assistance of an aquanaut, the aquanaut's job involves only organization of the research area proper -- selecting a site, setting up equipment, connecting the equipment to recording devices on board the undersea habitat or on the surface, and thereafter -- periodic servicing of the instruments set up at the research site. On the whole, however, collection of information proceeds without the aquanaut's participation. An example of a site of this kind is the Sealab program "Benthic" "undersea weather station."



Hydrolab program biological research site, for the purpose of evaluating the effectiveness of bottom traps under various conditions.



Closed breathing-cycle diving apparatus manufactured by General Electric is very popular with American aquanauts

Key:

1.	Oxygen tank	5.	Breathing mixture oxygen content detecting elements
2.	Power supply	6.	Inert gas tank
3.	Breathing bag	7.	Frame
4.	Breathing mixture composition electrical control unit	8.	Breathing mixture composition indicators
		9.	CO_2 absorber unit

Of course the above classification far from exhausts the list of different types of research areas. For example, there exist two-dimensional research areas -- set up on the seabed surface (geological), oriented vertically ("Chernomor" program masts with hydrooptical instruments), or three-dimensional installations (the fish tank of the "Sadko-3" undersea habitat). Nevertheless one can state that research areas are generally similar within the limits of a single type. Therefore it is expedient to describe here only certain research sites which are most typical of their type.

As we just stated, the simplest type of undersea research site is an area designated for visual observation of the habits of fish and marine organisms. Such a site is located in the most typical seafloor area for the research task, selected by the observer. Aquanauts take measures in advance to ensure that their own presence or the nearby undersea habitat do not disturb the natural habits of the subjects of observation and do not frighten them.

For this reason the Tektite aquanauts liked the breathing apparatus manufactured by General Electric. This equipment, which operates on a so-called closed breathing cycle, is absolutely silent and permits the aquanaut to remain in the water for hours. With this same objective -- to keep the surrounding water undisturbed -- designers of the "Helgoland" undersea habitat provided for removal of waste products from the structure through a long hose extending more than 100 meters from the structure.

One of the teams working out of the "Chernomor" habitat determined that the radius of ecological influence of a habitat standing on the seafloor is 20 meters. Obviously any biological research area should be sited outside this zone.

It is a somewhat more complicated matter to organize study of the reactions of fish and other living organisms to artificial stimuli. The Sealab I aquanauts, for example, set up on the seabed an entire system of sources of different noises and light. It was believed that with the aid of this setup it would be possible to study the reaction of fish to sound and light, but they were unable to perform these investigations.

A typical example of artificially created biological research areas are sites designated for studying the reaction of fish and bottom-dwelling animals to artificial structures on the seafloor. Precontinent-1 and "Helgoland" aquanauts, for example, erected unique shelters of concrete cubes and cylinders. An entire man-made reef was built for FLARE program aquanauts.

The "Sadko-3" habitat fish enclosure can serve as an example of a three-dimensional biological research area.

The smallest biological research site was evidently utilized in the Precontinent-2 experiment. Aquanauts installed a transmitting TV camera and a motion picture camera above the hole of a crab selected as subject of observation. A receiver to the transmitting TV camera was mounted on the duty console in the habitat. If the person on duty saw anything interesting on the TV screen, he would start up the motion picture camera from the control console and record the events. A large quantity of unique motion picture frames on the crab's "habits" was obtained in this manner.

At the present time biological research sites are the least "equipment-studded," and visual observation is the principal method of obtaining scientific information from them; geological research sites require pure observations to a lesser degree; hydrophysical investigations, as might be expected, involve the most equipment, and the job of the team conducting such investigations consists chiefly in setting up the site and monitoring the equipment.

Setting up a research site is usually not limited to selecting the site and installing equipment. An aquanaut who is working at a site dozens of meters from the habitat for periods of several hours a day must have a shelter alongside the site where he can find refuge in case of failure of equipment, illness, etc.

Such shelters are utilized in practically all experiments: Tektite, "Helgoland," and "Chernomor." Differing in size and design, all contained an interior space filled with breathing mixture, telephone communications with the habitat, lighting, light beacons, viewing ports -- a little underwater house.

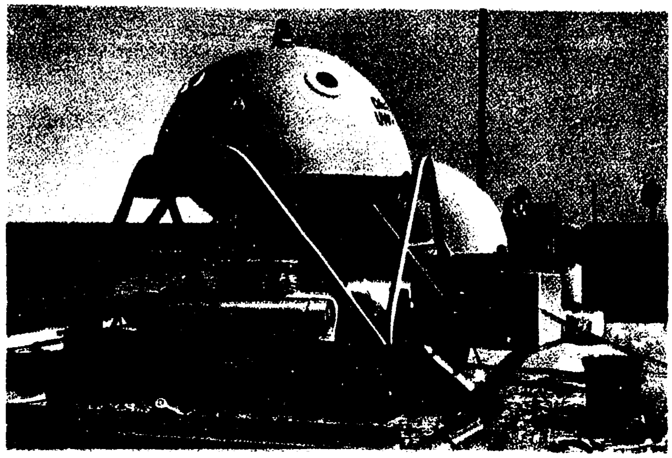
Shelter used in the Tektite program.

Perhaps the simplest of these was the shelter used with the Tektite undersea habitat, while the most complex was the shelter employed with the "Helgoland" habitat.

The shelters set up on the Tektite program research sites comprise a transparent acrylic hemisphere 0.9 m in diamater, raised 1.8 m off the seafloor. The bar walls of the shelter, fabricated of steel rods, are in the shape of a vertical cylinder. The space under the hemisphere is filled with air, so that an aquanaut who enters the shelter can disconnect his breathing apparatus and breathe the air in the shelter. Every shelter has a telephone for communication with the habitat and an emergency self-contained breathing unit.

In the Tektite I program five such shelters were set up at strategic points around the habitat.

The shelter used with the "Helgoland" habitat was designed and built by the Dreger Company. It is a dome-shaped steel structure mounted on a tubular frame which stands on the seafloor. The dome is in the shape of a hemisphere with a flat base, into which a diver's entrance well is mounted. Viewing ports are cut in the walls of the dome, and a flashing beacon stands on the dome top. The shelter has a self-contained life-support system, permitting two persons to spend several hours in the shelter. This structure was sited 38 meters from the habitat and connected to it by telephone cable.



"Helgoland" habitat emergency shelter.

Before initiating work activities, the entire seafloor surface around the habitat and on the research site is usually marked so that an aquanaut, wherever he may happen to be in the work area, always knows precisely where the habitat is, where which research site area is, and where a shelter is located. As a rule guide tips forming a system of squares, marking of which shows the aquanaut his location, are placed on the seafloor for this purpose. For night orientation, aquanauts usually employ "light lanes" -- lines of light beacons set up on the path from the habitat to the research area or shelter.

The aquanaut-investigator's work in water in the immediate vicinity of the target object greatly expands his investigation capabilities. But the degree to which an aquanaut is able to implement this potential is determined by the effectiveness of the instruments and equipment with which he works directly in the water, that is, instruments and tools designed to facilitate the collection of primary information on various parameters of the water environment and seafloor, collection of samples and specimens, mapping the seabed, etc. The aquanaut works at a depth of tens and hundreds of meters, under conditions of limited visibility, subjected to the effects of low temperature, currents and other adverse external factors, and therefore the instruments which he utilizes should be simple, durable and absolutely reliable.

On the whole the entire category of individual means of primary collection and accumulation of information can be divided into several groups:

means of surveying the target object. This group includes instruments for seabed mapping;

means of collecting information for subsequent processing on board the habitat or on shore -- for example, photographic or television equipment, devices for collecting soil and water samples, for trapping experimental subjects, etc;

instruments for obtaining characteristics of an object directly on the spot, without collecting specimens. Examples of such instruments include devices for measuring the mechanical properties of soils in situ, devices determining the optical characteristics of water, such as Secchi disks, color test charts, etc.

Some instruments used by aquanauts were designed for divers working from the surface, and some specially for aquanauts, but both groups of instruments have found their place in the arsenal of investigative means in equal measure.

During any submergence, regardless of the objective -- collection of samples, search for a research site, or simply acquaintance with the work area -- the aquanaut must determine the site depth, direction, time, distances, angles (for example, seabed gradient angles), and record observation results. Usually the aquanaut utilizes for this purpose a depth gauge, compass, watch, ruler, spirit level, note pad -- and he attaches all these things to his gear with cords, rubber bands, collars, etc. If to this we also add special gear -- such as samplers, cameras, specimen containers, etc -- the aquanaut, dangling equipment from all sides, becomes incapable of work.

The Sealab II aquanauts utilized a standardized plotting board, which carried a number of small items essential to the diver in his investigations. It was essentially a clipboard with measuring rules along the edges. It held a depth gauge, compass, goniometer, extensible carrier with spirit level, a pocket for a pencil, straps for securing the plotting board to the diver's belt, and a bracket for attaching additional items. Spirit levels were carried on both edges of the board.

The above-described plotting board, in combination with a compass card and tape measure placed on the seafloor, make it possible to obtain a plan map of the seabed. The compass card, a white plastic disk 0.61 m in diameter and bearing 1° graduations, mounted on a heavy, rigid base, is first aligned with the plotting board's magnetic compass in a north-south direction. In order to determine the bearing to any object on the seafloor, the aquanaut stretches the measuring tape from the center of the compass card to the object and measures the azimuth angle off the compass card and distance off the measuring tape. Two compass cards and two measuring tapes make it possible to map the seafloor by the trilateration method.

The described methods are effective in obtaining a map of a comparatively flat seabed. If seabed topography is complicated, however, and if it is necessary to know the relative depth of a given point on the seafloor, a differential depth gauge is normally employed to map the seabed. This device consists of a rubber hose with an elastic rubber container at one end and a pressure gauge at the other. The entire system is filled with oil. When operating the instrument, the storage container is secured to a deeper-sited object, and the pressure gauge is raised to a second object. Based on the position of the needle on the pressure gauge scale, the aquanaut can determine the difference in depths between the two points. The accuracy of such a system is approximately ±10 cm.

When working in fairly clear water, aquanauts triangulation-survey with the aid of an alidade and plane table. The plane table consists of a tripod support with attached metal triangle. A shaft runs through the center of the triangular platform. Turning on this shaft is a horizontal plotting board with three adjusting screws and two spirit levels. With the adjusting screws one can position the plotting board in a horizontal plane from the readings of the levels. An alidade with an open sight is mounted on the plotting board. This instrument is operated by two divers. One stands a surveyor's rod by an object, while the other sights the object's top and bottom points, determining its height, the angle between the rod sighting lines, and thus distance to the object.

In working in large areas hydroacoustic means of finding objects are the most expedient -- hydroacoustic beacons and direction finders or sonars. Sonar equipment is utilized fairly extensively in diving activities. We must state, however, that although the accuracy of modern sonar equipment under water is ±1 m at a distance of 100 meters, such equipment is very expensive at the present time.

The French company Thomson CSF recently began the manufacture of portable buoy-beacons and manual direction finders. A buoy can be placed at depths of down to 200 meters, either directly on an object or directly on the seafloor (in this case an anchor and float are attached to the buoy, which hold it a certain distance from the bottom). The buoy weighs 1.2 kg in air and 0.5 kg in water; self-contained operating time under water is approximately 1 month. The Thomson manual direction finder is in shape and size reminiscent of a traffic officer's baton; it is 39 cm in length and 6.3 cm in diameter. In air it weighs 0.95 kg, and has neutral buoyancy in water. One end of the device contains a hydrophone, and the other a compass and two lights. When searching for the target, the aquanaut holds the direction finder in front of himself. If the ultrasound source is to the right of the device, the right light ignites, and if it is on the left -- the left light. If the direction finder is pointed straight at the buoy, the lights come on alternately, and at this moment the aquanaut can take a bearing from the compass card. Maximum detection range of the beacon buoy is 750 meters.

If there is no beacon on the object, the aquanaut utilizes active search gear: an ultrasonic signal transmitter and a receiver-direction finder, mounted in a single unit. Probing with a narrow ultrasonic beam and picking up the echo with the direction finder, the aquanaut can determine not only bearing to an object but also distance to it and its size.

Modern sonars are unwieldy and inconvenient at the present time. The AN/PQS-IB sonar made by Dalmo-Victor (utilized by the Sealab II aquanauts) is operated by two divers. It weighs approximately 10 kg in air, and in water it has a positive buoyancy of 225 grams. The operator determines bearing to the object by volume of sound in the headphones. Maximum signal level corresponds to the precise bearing of the reflector axis to the object. Range is determined by pitch of the tone in the headphones. If the object is at a range of 18 meters, for example, a tone with a pitch of 25 Hz is audible in the headphone, while if the range is 90 cm, the tone will have a frequency of 250 Hz. According to published information, this instrument is capable of detecting such an object as a bucket, for example, at a distance of up to 110 meters, and a tin can up to 18 meters.

Hydroacoustic means of finding objects are particularly extensively employed in studies of migrations of little-mobile bottom-dwelling organisms, such as lobsters. Tektite program aquanauts secured to the backs of lobsters miniature sonar beacons, and then followed their movements during the course of several days with the aid of sonar units.

The direct search for an object and recording of its position in space is only part of the overall task of investigation. Upon finding an object, the aquanaut should be able to process it in such a manner that he can obtain the desired result either immediately, on the spot, or later, in the habitat. The diversity of forms of processing of an object, determined by the extraordinary diversity of research objects and research investigations proper, makes it impossible to give a full description of all information collection tools used by aquanauts. They can, however, be subdivided into two large groups.

The first group includes means of collecting visual information on the general form or behavior of an object. These include various still and motion picture cameras, and videotaping equipment. The second group includes devices for collecting samples of water, soil, and catching living organisms, including fish.

Let us examine in greater detail the most typical individual information collecting devices used by aquanauts.

There exists today a countless variety of still and motion picture cameras intended for underwater use. As far as is known, however, two cameras specially designed and built for underwater photography have been the most successful. The first is the famed Calypso-Photo camera, designed by the Cousteau team. In contrast to the majority of underwater cameras, which are nothing more than a conventional camera for land photography encased in a watertight box, the Calypso-Photo camera was designed from the outset for underwater photography.

This camera is designed for use with a standard 24 x 36 mm frame on a 36-frame 36 mm roll. The camera is very small in size -- approximately 130 x 90 x 35 mm. It has slight positive buoyancy in water.

Apparently the best of currently-existing wide-format cameras is the RS-770, built by the U.S. company Hydro Products, in conjunction with the U.S. Navy Electronics Laboratory. This camera was extensively utilized at depths of up to 90 meters in the Sealab II experiment. The camera also comes with an electronic flash attachment.

Advances in electronics have made it possible to design and build small underwater TV transmitting cameras. The high sensitivity of modern electron-beam tubes makes it possible to build underwater TV cameras with greater sensitivity than the human eye.

Instruments for direct measurements of the characteristics of a target object have been most extensively utilized in geological studies, since remote measurements of seabed parameters of interest to geologists are made difficult by the static character of an object: as a rule a small number of measurements is required at each given point, after which the aquanaut moves to a new work site.

The "Chernomor" aquanauts utilized a profilograph to determine seafloor ripple profile. This instrument consists of a frame resting on two supports. Aluminum rods are positioned vertically on the frame at 2 cm spacings. A spring-loaded catch impedes free vertical movement of the rod. When the instrument is being set up, the rods are raised to the uppermost position and secured in that position. Then the aquanaut places the instrument in the required position on the seafloor and releases the catch. The freed rods gently drop to contact with the seafloor surface, after which their position is again secured. The envelope curve formed by the lower ends of the rods reproduces the profile of the seabed topography form being studied.

Sealab program aquanauts utilized to measure the shearing strength of seabed marine sediments a hand instrument consisting of a head formed by two plates intersecting at a right angle. They are secured at one end of a bar, with a spring-loaded turning handle on the other end. The aquanaut gently introduces the plates into the soil, and then turns the instrument by the spring-loaded handle. As the handle turns, the spring compresses and transmits increasing force to the bar and to the instrument head which has been inserted into the soil. When the force exerted on the head exceeds the load-bearing capacity of the soil, the head begins to turn. The position of the handle relative to the indicator at this moment indicates the soil's shearing strength.

Measurments in situ as a rule provide information only on certain physical-mechanical soil properties and their microtopography. A more detailed study of soils can be performed only in the course of laboratory analysis of aquanaut-collected samples.

Manual samplers utilized by aquanauts are of quite diversified function, design and size.

Devices akin to water samplers, and containers with shutting tops would be used to collect samples of water or "liquid soil."

On a number of undersea habitat missions aquanauts employed core samplers to collect samples of loose soils. These are of varying design, but all operate on a single principle. The aquanaut forces by hand into the soil a hollow tube, which he then removes from the seabed together with soil which has entered the tube's interior cavity. Placing safety caps on both ends of the core-containing tube, the aquanaut places it in a carrier. The length of a core taken in this manner depends on the character of the seabed and the skill of the aquanaut collecting the sample, and ranges from 20 to 30 cm. Usually a tube-type core sampler is equipped with a removable handle for greater ease of operation.

Aquanauts have successfully employed a manual pneumatic percussion sampler in collecting specimens of seabed loose soil and silt. The vibration mechanism is powered by compressed air from breathing apparatus tanks. This sampler can obtain cores 25 mm in diameter and several tens of centimeters in length.

Tektite and FLARE program aquanauts used an electric hand drill to obtain specimens of rock and coral. The drill set includes two diamond-bit drill bars. With an electric drill the aquanaut can collect a core 18 mm in diameter and 35 cm in length.

On the whole the arsenal of individual aquanaut means of investigation is quite diversified, and as a rule new instruments are designed and built for performing new tasks. As experience indicates, however, most frequently underwater experiments are interrupted because instruments for individual collection of information prove ineffective in those conditions in which they are utilized. It is therefore very important that instruments not only be designed by competent specialists but that they also be thoroughly tested under conditions maximally approaching actual use conditions, and before an underwater experimental program actually begins.

EPILOGUE

A unique anniversary will be celebrated in September 1977 -- the 15th anniversary of submergence of the world's first undersea oceanographic habitat, the "Diogène," of the "Precontinent" program. What have aquanaut-oceanographers accomplished during these years?

The first period, of enthusiasm with a new method of working and conducting research under water -- a period when enthusiasts believed that all or at least the overwhelming majority of oceanographic tasks could be performed solely by putting man under water -- is past. Today we have a more realistic idea of what an oceanographer can actually accomplish under water and what place this method of studying the ocean occupies in the overall arsenal of research means. What can we expect in the immediate and more distant future?

Prediction has always been a very delicate operation. It is difficult to approach scientific and technological advance with today's measuring sticks, although a correct forecast significantly facilitates the entire process of further development.

Evidently the majority of scientific programs based on utilization of undersea habitats will be focusing in the immediate future on study of depths of several tens of meters -- depths with the most intensively occurring processes and with the steepest gradients.

Evidently further advances in undersea habitats of this medium-depth category will be aimed at improving undersea habitat systems which provide habitability and capability to conduct scientific programs, as well as the development of new sources of energy for undersea habitats. The latter is especially important, since power supply remains the Achilles heel of all habitat work programs.

The possibilities of employing undersea habitats in oceanography, however, are not limited to medium depths. There already exist, and there will be more, certain particular tasks the accomplishment of which requires oceanographers to work at greater depths as well, right down to maximum depths beyond which man cannot dive. The most typical example of such tasks is installation, adjustment and servicing of scientific research equipment.

The present level of technology permits design and construction of undersea habitats with a working depth of several hundred meters. The question is at what depth will man be able to work in the sea, and what period of time?

Usually it is difficult to obtain an unequivocal answer to such a question. Acquisition of diver working depths takes place in several stages, and characteristic of each stage is a depth and working time at that depth.

Man living and working at depths down to 180 meters has already become a reality. French and American scientists have performed successful experiments with personnel living and working for periods of many days at depths of 250-300 meters, but these depths are not yet routine for diving activities.

Deep-water "dives" have been made in land simulators to even greater pressures. "Dives" to a depth in excess of 300 meters have been made in hydrocompression complexes -- pressure chambers some of the compartments of which are filled with water and in which deep-sea diving conditions are simulated with a high degree of authenticity (water pressure, temperature and salinity, clarity).

In pressure chambers, which are purely laboratory installations, people have remained for several days under pressure of approximately 600 meters of water column -- under a pressure of more than 60 atmospheres!

Evidently in the near future man will be able to work at these depths in the sea as well, and if this comes to pass, diver-oceanographers will be performing their research at these depths. It is not yet clear what technical devices will give them this capability. Depths of 1500 meters constitute a qualitatively new stage in the evolution of diving, and it will require qualitatively new technical solutions.

But all this is a matter of the distant future. In the meanwhile oceanographer-aquanauts see as their immediate task thorough study of the phenomena and processes taking place at medium depths -- several tens of meters, depths the mastery of which can make a significant contribution to the nation's economy.

Appendix. Concise Data on Experiments With Undersea Habitats, 1962-1976

Habitat Name	Country	Year	Depth, m	Size of Crew	Displacement, tons	Support	Body of Water	Tasks
"Man in the Sea"	USA	1962	61	1	2.5	Vessel	Sea	Physiology
"Diogène" (Precontinent-1)	France	1962	10	2	25	Vessel, shore	Bay	Physiology
"Sea Star" (Precontinent-2)	France	1963	10	5	90	Vessel	Sea	Oceanography
"Rocket" (Precontinent-2)	France	1963	25	2	20	Vessel	Sea	Oceanography
SPID	USA	1964	132	2	5	Vessel	Sea	Physiology
Sealab I	USA	1964	59	4	70	Vessel	Sea	Navy ERUTR*
Sealab II	USA	1965	61	3x10	184	Vessel, shore	Sea	Navy ERUTR, oceanography
Precontinent-3	France	1965	100	6	130	Shore	Sea	ERUTR, oceanography
"Glaucous"	UK	1965	10	2	13	Shore	Harbor	Sport
"Ikhtiandr-66"	USSR	1966	10	2	5	Shore	Sea	Sport
Hydrolab	USA	1966, 1970-1976	12.5	3	25	Power buoy	Sea	Oceanography
Caribe-1	Czechoslovakia-Cuba	1966	15	2	5.5	Sea	Vessel	Sport
"Meduza-1"	Poland	1967	to 24	2	3.7	Shore	Lake	Sport
"Permon-3"	Czechoslovakia	1967	10	2	5	Shore	Lake	Sport
"Khebros"	Bulgaria	1967	10	2	18	Shore	Lake	Sport
"Ikhtiandr-67"	USSR	1967	10	5	28	Shore	Sea	Sport
"Sadko-2"	USSR	1967	25	2	32	Shore	Sea	Oceanography
"Meduza-2"	Poland	1968	to 25	2	9	Vessel	Sea	Oceanography
BACH-1	FRG	1968	10	3	20	Vessel	Sea	ERUTR
"Malter"	GDR	1968	8	2	14	Shore	Lake	Sport
"Robinsub"	Italy	1968	10	1	7.5	Shore	Sea	Sport
Edalhab	USA	1968,	9	3	20	Shore	Lake	Sport
		1972	14	3	20	Vessel	Sea	Oceanography
"Ikhtiandr-68"	USSR	1968	11	4	15	Shore	Sea	Sport, Oceanography

Appendix (cont'd)

Habitat Name	Country	Year	Depth, m	Size of Crew	Displacement, tons	Support	Body of Water	Tasks
Chernomor	USSR	1968-1974	14-30	5	80	Vessel	Sea	Oceanography
Tektite	USA	1969,	15	4	160	Vessel	Sea	Oceanography
		1970	15	5	160	Vessel	Sea	Oceanography
"Atlantida"	Italy	1969	15	4x3	44x3**	Vessel	Lake	Sport
"Sadko-3"	USSR	1969	25	3	49	Vessel	Sea	Oceanography
"Helgoland"	FRG	1969 1972-1974	23	3÷4	64	Power buoy	Sea	Oceanography
"Sublimnos"	Canada	1969	9	2	15	Shore	Lake	Oceanography
"Shelf-1"	Bulgaria	1970	21	3	40	Vessel	Sea	Oceanography
("Idzher")	USA	1969-1971	157	6	380	Vessel	Sea	ERUTR
"Seatopia"	Japan	1972, 1973	100	4	85	Vessel	Sea	ERUTR
"La Chalupa"	USA	1972, 1973	30	4	140	Power buoy	Sea	Oceanography

* ERUTR -- Emergency Rescue and Underwater Technical Work.
** Three four-person living quarters compartments displacing 44 tons each were employed.

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CSO: 8044/1330

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APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000300020041-1